

# Selected Conference Proceedings

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# 1. SUSTAINABLE AND RESILIENT INFRASTRUCTURE: HOW AN INTEGRATED, PLAN-LED APPROACH IS VITAL FOR LONG-TERM AND INCLUSIVE OUTCOMES.

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**ABSTRACT.** This paper starts by exploring how resilience relates to infrastructure. Resilience is both a property of something, but also what it connects to: what it is for. This wider context extends from an individual structure such as a bridge, to whole infrastructure systems and how they interact. These connections are affected by climate change, which is increasing disaster risks and other slow-onset impacts. Longer-term resilience requires economic pathways to prioritise sustainability and inclusiveness over infrastructure-led growth, which increasingly, due to resource constraints, tends to increase inequality. This requires positive plan-led approaches that constrain infrastructure within carbon and resource budgets, and link to spatial planning. Resilience is then responding not just to disasters but climate and environmental limits. And in the realism of accepting that increasing future disasters are inevitable but maximising equitable carbon emissions reduction needed to avoid overall climate catastrophe it is a concept that can engender hope.

**Keywords:** Resilience, Infrastructure, Climate, Sustainability, Development, Hope.

## 1. INTRODUCTION

As I write this Hurricanes Harvey, Irma and Jose are breaking records as they leave a string of destruction in their wake. Climate change is magnifying the severity and impact of natural hazards now – and as we continue to stoke global warming most likely to cause even greater impacts in the future. This requires a response that results in a different approach to how we make long-term decisions around what kind of future we invest in and build. How can investment in a bridge, designed to last 120 years be resilient over its whole design life? How does resilience to the vision for a city and its linked infrastructure and development plans? Can rapid urbanisation of a city in a coastal flood plain be resilient as sea levels rise? How can urban areas be resilient as they concentrate and consume resources and energy on a global scale? In this context, what does resilience, in relation to infrastructure really mean?

The rest of this paper is structured as follows:

- Section 2 proposes that there is a danger of too narrow a consideration of resilience. In the context of infrastructure there is a need to ensure that this is not just the resilience **of** infrastructure but also what infrastructure development is **for**.
- Section 3 explores the impact of considering resilience over the longer-term, and how this implies a close relationship between resilience and sustainability.
- Finally, section 4 explores the consequences of planning infrastructure development that is both sustainable and resilient. This highlights the need for different investment choices, spatial planning to link economic decisions to social and environmental outcomes and for redirecting overall development pathways.

- This paper builds on research to summarise and signpost overall approaches to resilience internationally for the UK Department for International Development [1].

## 2. THE RESILIENCE OF INFRASTRUCTURE INVESTMENT

### 2.1 Distinguishing between the resilience of infrastructure and what it's for

Resilience brings together disaster risks and climate risks. The widely accepted UN definition for resilience is:

*“The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions”.* [2]

The resilience of infrastructure is reflected in the Sustainable Development Goals, notably Goal 11, which sets a target for provision of resilient infrastructure and Goal 9, which aims to make cities and human settlements inclusive, safe, resilient and sustainable [3]. These goals require infrastructure to be resilient in two ways:

- Firstly, **the resilience of the infrastructure itself** – and how it contributes to economic benefits; and
- Secondly, what does **infrastructure affect and what is it for**. This considers how infrastructure affects the wider resilience of other infrastructure systems, as well as the sustainability, resilience and livelihood options of individuals, households and communities: directly and indirectly, now and into the future.

This paper explores the importance of both these aspects. How these two aspects are applied to different scales of infrastructure are explored in section 2.2, before exploring wider aspects of resilience in section 3 below.

### 2.2 Resilience of infrastructure: from infrastructure elements to a nexus of infrastructure systems.

Firstly, for infrastructure, and wider infrastructure systems, to be resilient, they must be resilient in and of themselves. This depends on different aspects, including:

- **Technical specification.** This is reflected in its design and construction;
- **Serviceability.** Infrastructure systems should be planned to be operational at an *appropriate* level of serviceability, such as during or immediately after a disaster (which could entail a shift in performance specifications). Also it is vital to ensure that existing assets are properly maintained – and improved to cope with increased shocks and stresses over their lifetime; and
- **Institutional support.** The institutions that are responsible for building and maintaining this infrastructure should have the capacity and skills needed.

These aspects are highlighted for transport infrastructure in Fig. 1.

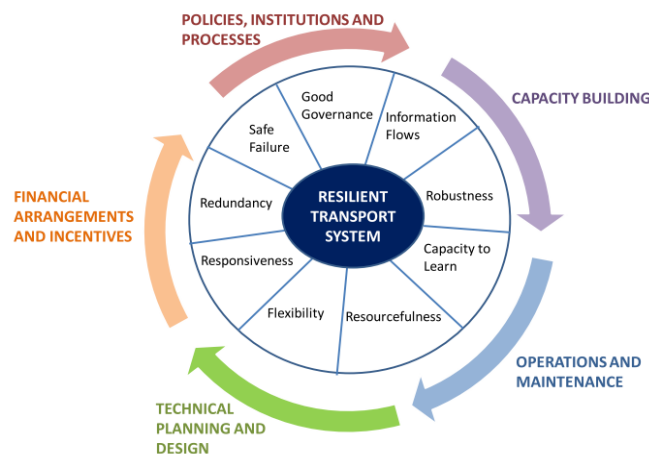
These aspects of resilience apply at different scales, such as:

- An **infrastructure element** – a bridge;
- An **infrastructure system** – a transport network; and
- **Connected infrastructure systems** – how different systems interact.

Firstly, consider the resilience of a single piece of infrastructure: a **bridge**. A bridge must itself be resilient to disasters, and ongoing hydro-meteorological (climate) changes. For any given disaster risk, resilience can be realised in different ways. For example a bridge could be more resilient to increased flood risk by a combination of:

- Raising the level of the bridge so it is above the worst predicted flood event;
- Upstream measures (e.g. re-afforestation) to reduce this flood event;
- Improving maintenance and procedures for how to protect it in the case of a flood event, such as improved scour protection so river debris does not build up under the bridge and undermine a bridge support due to scour; and/or
- Designing the bridge so elements that are most exposed fail first, so that they can be easily replaced without damaging the main structure. For example, a lightly secured timber boarded deck could be designed for *safe failure*, reducing the risk of the rest of the bridge being damaged.

This shows that resilience of infrastructure includes both physical properties and system properties (including how it is operated and maintained). Different resilience aspects for a **transport infrastructure element or system** are highlighted in Fig. 1.



**FIGURE 1.** Resilience Aspects of Infrastructure Itself. Source: [4]

Secondly, consider the resilience of an infrastructure system. The choice of how to make a bridge resilient will also affect the degree to which access is sustained for this link in the wider transport network. Failure of the bridge could reduce access between two sides of a river (depending on the extent that alternative routes or modes of transport are available), leading to two communities being separated from each other. Such alternatives increase *redundancy* in an infrastructure system, reducing overall vulnerability to extreme events. This means resilience extending from a focus on aspects of an element of infrastructure to its wider impacts.

Thirdly, it is increasingly important to consider not just the resilience of individual infrastructure elements (e.g. a bridge), or even infrastructure systems (e.g. land-based transport network) but how overall infrastructure systems interact with each other. Knowing how infrastructure systems affect each other, could affect the investment priorities of different types of infrastructure.

Savage et al [5] highlight the way that energy, water and land systems are interconnected. This is also reflected in ways in which different infrastructure types interact, when faced with disasters and climate change. For example, in 2015, flooding in Lancaster of an electricity sub-station led to a mobile phone black-out and power outages across the city. The hinges of electronic entrance doors into student accommodation had to be cut using handsaws to gain entry. Some hotel rooms were not able to be used as temporary accommodation for people whose homes were flooded as they had electronic card-operated doors. Meanwhile, the wind turbine at Lancaster University continued to turn and generate electricity but this could not be used as there was no local off-grid system to provide back-up power. This is reflected in this extract [6].

*“The impacts [following the flood event on 5-8 December 2015] strike me as being quite different from the power blackouts I experienced as a child during the 1970s and 1980s, perhaps because they were less anticipated, perhaps because our dependence these days on the internet and telecommunications is profound, or perhaps because one impact led to another in a cascade.”*

This leads to a consideration not just of the resilience of infrastructure itself, but how this affects the sustainability and resilience of the wider society and environment. For example, increasing the resilience of ‘critical infrastructure’<sup>1</sup> to flooding may increase flood risk in other areas. Therefore, a focus on the climate (and disaster) resilience of infrastructure may not only change the nature of infrastructure itself, but lead to a shift in the mix of infrastructure needed for sustainable communities.

Similarly, there are interconnections in how different infrastructure sectors contribute to carbon emissions, and impact long-term sustainability and overall resilience of built environments, such as cities in vulnerable areas. The IPCC working group 3 chapter on human settlements, infrastructure and spatial planning [7] notes that:

*The global expansion of infrastructure used to support urbanisation is a key driver of [greenhouse gas] emissions across multiple sectors. Due to the high capital costs, increasing returns, and network externalities related to infrastructures that provide fundamental services to cities, emissions associated with infrastructure systems are particularly prone to lock-in ... especially for energy and transportation Infrastructure.*

OECD funded research [8] sets out the need to focus not just on the climate resilience of infrastructure, but to prioritise infrastructure for low-carbon and climate resilient development. For example, investment that is climate resilient and low-carbon will shift investment priorities between sectors, increasing (renewable) energy and water investment. Increasing overall built environment resilience (e.g. for a rural and/or urban area) will require new solutions, to leapfrog current infrastructure solutions or provide resilience where it is lacking. For example, renewable energy is both a more resilient *and* sustainable energy solution (and also more cost-effective) than the diesel generator sets used by the UN in most refugee camps. Similarly off-grid and decentralised renewable energy systems can now run at lower unit costs than large-scale thermal power plants.

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<sup>1</sup> Critical infrastructure is defined as [2]: ‘The primary physical structures, technical facilities and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extremes of an emergency’.

This focus of not just the resilience of an investment but how it interconnects with the existing built (and natural) environment, communities and ways of life: what development is *for*. This means that resilience does not just require changes to the specification of the physical new (and existing) built environment, but a completely different approach to planning and investment, and one that addresses disaster and climate resilience together. This is explored below, and requires long-term thinking.

### 3. LONG-TERM RESILIENCE

#### 3.1 How does climate change impact the disaster management cycle?

The traditional disaster management cycle, sets out how disaster preparedness, relief and recovery are needed – for one disaster at a time (see Fig 2.).

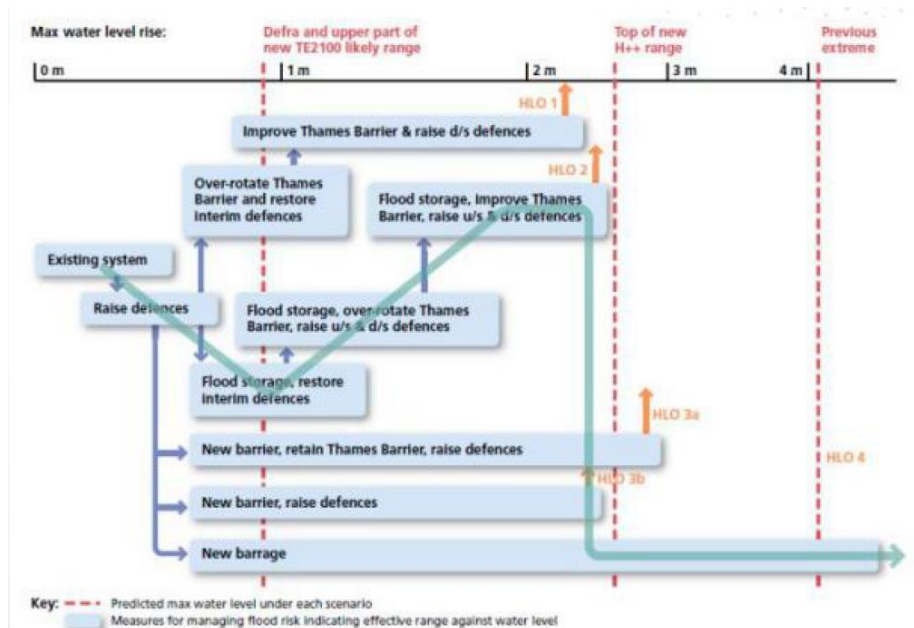


**FIGURE 2.** Disaster Management Cycle (Recovery from Shock). Source: Author

Best practice considers how this cycle should increase resilience as households ‘bounce back better’ [9] and infrastructure is ‘built back better’ [10]. But this focus on disasters alone, does not recognise the increasing frequency, severity and unpredictability of climate-related disasters, or slow-onset climate impacts such as temperature rise and sea level rise. A climate disaster cycle must look further into the future. Climate change will progressively reduce resilience. Increasing recovery costs (in social and environmental, as well as financial terms) will change what infrastructure is affordable. The IPCC [11] highlights that a focus on improving financial resilience (such as through insurance) can neglect wider resilience, especially as climate impacts become more widespread, and not drive the transformation needed to improve longer-term resilience.

#### 3.2 Longer term thinking.

Longer term thinking changes decision making. Ranger [12] cites the Thames 2100 project [13], which found that climate risk varies significantly with time. This means that extending the infrastructure design life changes the preferred infrastructure choice (see Fig. 3). The researchers (UK Met Office) also highlighted that as climate projections will (also) change, the solutions chosen should be adaptable.



**FIGURE 3.** Sufficiency of Solutions Depends on Design Life. Source [12].

This conclusion should be applied to physical (including urban) planning. Longer-term planning is needed for both the location and type of infrastructure, housing and wider built environment choices. In most places planning is not sufficiently long-term (or enforced). For example, dredging for real estate development in the flood plain on one side of Dhaka, whilst a dyke only protects the other side from flooding is not sustainable. Dasgupta et al [14], studying how Bangladesh's infrastructure might be climate proofed, concluded by highlighting the need to focus not on the gap in infrastructure for growth but that to address an outstanding climate adaptation deficit.

A different approach is needed for the built environment to better withstand disasters in future. As the extent of climate mitigation will affect long-term climate impacts, an effective strategy to deliver long-term resilience requires climate mitigation and adaptation to be delivered together. One example of this approach is in Kolkata, whose city corporation has declared it will adopt a new development pathway that is low-carbon and climate resilient [15]. However, unless such plans are sufficiently precautionary and long-term in terms of both likely climate impacts and carbon emissions reduction they might not ensure resilience in the longer-term (see Box 1).

**Box 1. The need for a precautionary approach to future climate risk: Kolkata.**

Kolkata's 2015 plan is based on data from the 2007 Fourth Assessment of the IPCC (AR4). As this only considers 0.27m of sea level rise (by 2050) it very likely underestimates sea level rise as it underplays the impact of future thermal expansion of oceans, glacier collapses on Greenland, and accelerating Antarctic melt (From 2012 over 60% of new sea level rise estimates account for such contributions, reflecting new science set out by [16]). For example, the 2017 USA National Oceanic and Atmospheric Administration [17] presents the current knowledge of Antarctic and Greenland positive feedbacks modelling and highest rates of plausible additional global mean sea level rises, now project a 2m sea



level rise by 2100 under the “business-as-usual” scenario RCP8.5. Planning for Kolkata’s future based on decade-old data could lead planners to underestimate future sea level rise risks, as well as the associated economic losses of floods worsened by high sea level increases.

Therefore, such an approach requires taking a *different and longer-term* approach to ensuring future livelihood and infrastructure resilience. This includes both planning for greater greenhouse gas emissions reductions to strive together globally to meet the lowest global carbon emissions cap, while being realistic about what the current climate projections could entail.

In Bangladesh, this approach might challenge the presumption that development will continue to be concentrated around the capital, Dhaka. Reviewing the extent to which urbanisation (in particular, in such a climate vulnerable location) is sustainable and resilient in the long term will require a different development pathway, not just at the city but at country and international levels.<sup>2</sup>

Kennedy and Corfee-Morlot [18] propose comprehensive national strategic plans coupled with national climate change goals that prioritise investment differently. Such an approach for spatial planning in the most vulnerable parts of Bangladesh is proposed in the Bangladesh Delta Plan 2100 [19], but it is not clear to what extent this will change the current trends in urban and infrastructure development. An alternative strategy could direct growth away from large cities, in a sustainable manner. Such an approach requires resilience to be part of an overall planned goal: ***sustainable, inclusive and resilient***.

## **4. SUSTAINABLE, INCLUSIVE AND RESILIENT ECONOMIC PATHWAYS**

### **4.1 Combining social and environmental goals: sustainable, inclusive and resilient**

As outlined above, maximising climate mitigation (greenhouse gas emission reductions) will reduce some of the increasing scale and magnitude of future climate disasters [20]. This in turn requires us to shift to ways of living across the world that can be sustained within environmental limits. This requires a planned approach: not just spatially but in terms of energy and resource use across all sectors - to shift the scale of resource use globally to within our planet’s stock of sustainable and renewable resources [21]. Thus for resilience to be sustained, it must be environmentally sustainable. This requires a reduction in the overall level of resource consumption (as well as greenhouse gas emissions), which could either:

- Reduce the resilience and livelihoods of the poorest (households, geographic areas, countries) first, increasing inequality. To some extent this is already happening [22], and will likely increase social tensions and global instability; or
- Create more resilient communities and economies (both within and between countries) by increasing equality at the same time as reducing resource and energy consumption, which could improve the wellbeing of all [23]<sup>3</sup>.

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<sup>2</sup> As some (particularly low-lying and hot) countries become increasingly precarious and/or inhabitable.

<sup>3</sup> Some argue that it is best to reduce poverty first and then climate and environmental issues later [42], but this risks locking-in climate emissions through infrastructure choices, as considered below.

Achieving this second option requires a focus on improving the livelihoods (social sustainability) of the poorest whilst reducing the resource and energy use (environmental sustainability) of middle-income and richest households and societies globally. Thus, a resilient approach must also be inclusive.

This aim is consistent with existing long-term national strategies such as the UK sustainability strategy's twin aim to improve quality of life for all within environmental limits: [24] as well as various global agreements on climate change [25], disaster resilience [26] and wider sustainability [27], [28]. However, it is not reflected in mainstream political decision making which prioritises economic growth and infrastructure investment, using tools such as cost-benefit analysis. Therefore, whilst planning to keep our urban areas (and wider economies) within climate limits, sustainable, inclusive and resilient is both feasible and consistent with stated goals, it is not currently sufficiently integrated into our decision making.

Improving the livelihoods (and resilience) of the poorest whilst reducing overall climate emissions and impacts requires different priorities to underpin economic decisions. This requires richer countries, urban areas and households to reduce their (still increasing) levels of consumption of environmental resources most. This will require a shift from providing *more* infrastructure (which tends to lock-in higher mobility and consumption for those able to afford it most) to investing in *different and less* infrastructure overall.

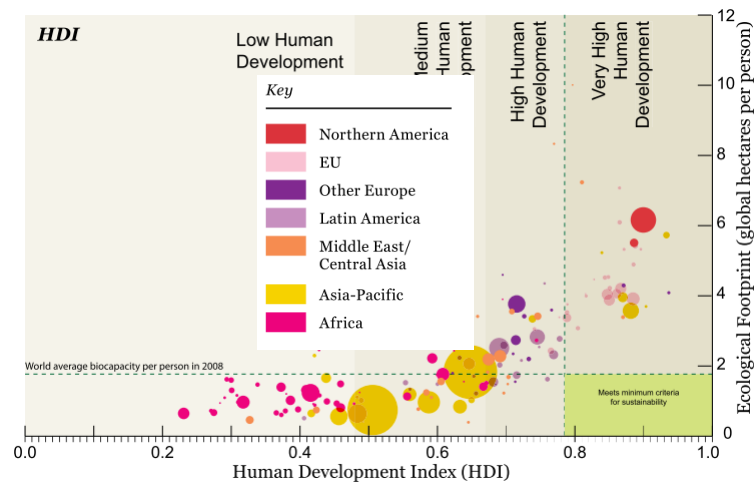
Only limited infrastructure improvements are needed to improve the quality of life and happiness of the poorest now - as research shows that quality of life [29] and happiness [30] only increase up to a certain consumption level. This means a wider shift in infrastructure provision can focus on enabling more sustainable and resilient employment and ways of living, that enable better longer-term freedom and security. So, before planning how to *adapt* infrastructure and wider development priorities<sup>4</sup> to be as *resilient* as possible, we should plant to unlock economic pathways and allow them to be sufficiently socially and environmentally sustainable.

Mapping outcomes of different existing approaches (now and historically) indicates what economic pathways are sustainable and inclusive – and therefore have the potential to also be resilient. WWF [31] contrasts the social and environmental metrics for different countries, and highlights that it is possible to be sustainable environmentally whilst having good social outcomes (contrast countries in Fig. 4).

Applying this at different scales from the household and community, to city, region and global scales highlights that reducing the scale of infrastructure tends to improve sustainability and resilience. To reflect this in decisions by governments and others as to how much and what type of infrastructure is needed, a different goal is needed.

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<sup>4</sup> As well as production and consumption.



**FIGURE 4.** Ecological Footprint against Human Development Index. Source: Adapted from [31]

## 4.2 Sustainable and Inclusive Planning: resilient and multi-sector approach

The section above highlights how sustainability and inclusiveness as *outcomes* are pre-requisites for resilience (which is a *function of the adaptability* of a development pathway, or economy) in the longer-term as illustrated in Table 1.

**TABLE 1.** Relating sustainability, inclusiveness and resilience to the process and end goal of (economic) development. Source: Author

	Process: Development	End Goal: Sustainability
<b>Sustainability</b>	Building uses significant resource and 'embodied' carbon – while changing the scale/nature of future resource/energy use.	Sustainability means staying as far as possible within environmental limits. This includes resource and energy consumption in use, and to maintain/replace existing assets.
<b>Inclusiveness</b>	Sustainable economy links process to 'sustainable' end state	
	Ownership of goals, inputs and process; assets and access	
<b>Resilience</b>	Internal system properties. Resilience <b>of</b> . Flexible and adaptive to shocks and stresses, recovery	External system properties. Resilience <b>for</b> . Links to outcomes wider than specific infrastructure element/system/location/purpose.
Resilient process leads to more sustainable and inclusive future		

It is vital to consider sustainability, inclusiveness and resilience together, as the degree to which a development pathway is resilient will affect how it can overcome disaster events and changes to underlying conditions while still meeting goals – and vice-versa.

Considering these aspects together, resilience, as part of a pathway towards a sufficiently sustainable and inclusive future, could be described as transformational [32]. This means envisaging resilience *for* a better future for all –engendering a step-change rather than incremental change in development processes, and outcomes.

One key aspect of sustainability is the extent to which investment is used to drive an unsustainable or sustainable economy (in terms of resource use, energy and carbon emissions, employment and equity). Instead of increasing infrastructure that maximises economic returns, infrastructure investment should be limited to that which delivers sufficient reduction of carbon emissions on energy and resource invested whilst also increasing inclusivity, and being sufficient adaptable to withstand potential disasters and future slow-onset changes. This means that investment choices and urban planning that is more about facilitating better quality of life with *fewer* resources.

Different decision making tools and approaches are needed to plan development that *reduces* total resources and energy use, within a carbon budget. This should limit investment in infrastructure to that which reduces future emissions (e.g. renewable energy), avoiding that which tends to increase future carbon emissions. This applies especially to major urban capital investment decisions as these can have lasting impacts in terms of land-use and carbon emissions – ‘locking in’ carbon emissions for many years to come, while ensuring that people live in a certain location which may become less resilient due to sea level rise for example (see Fig. 5).



**FIGURE 5.** Time Periods for Investment Decisions. Source: [33].

This means that aspects that currently treated as externalities when investment is prioritised economically will become central. This will change:

- **Time horizons.** Investments by the World Bank typically have  $\geq 12\%$  ROI, so typically payback in less than ten years, much shorter than most infrastructure lifespans. Sustainable investment means decisions look *beyond* the physical lifetime and ensure the nature and scale of investment stays within environmental limits.
- **Social and environmental opportunities, not just risks.** Instead of de-risking investment through screening and mitigating for bad social and environmental impacts, the focus will be to maximise social and environmental outcomes. This will include improving sustainability, inclusiveness and resilience.
- **Return on carbon/energy/resource invested.** Individual investments will be carbon constrained. This should consider both the initial ‘capital outlay’ in resources and energy associated with the investment, as well as in-use expenditure/creation of resources and energy. A sustainable economy means that more investment will be geared to transitioning and adapting existing assets, to support and enable different forms of production (green

enterprises, leapfrogging current technologies and ways of organising) and consumption (lifestyle choices), rather than extending the built environment further.

- **Multiple priorities.** Urban infrastructure must be within resource and energy (greenhouse gas emission) limits and account for air pollution. The New Climate Economy Group notes that once these externalities are costed, it is likely that there will be less growth and more compact cities, as low-density housing is not climate smart development. [34]
- **Linkages, not trade-offs.** Environmental and climate impacts will not be traded against resilience or social outcomes – solutions will be chosen that work well together. Connected outcomes include how things are connected *physically*: live-work communities, transit-orientated development.

This means investment decisions must sit within a shared vision, strategy, spatial plan and economic strategy. This in turn requires greater, more inclusive participation so that different infrastructure systems and future enterprises and operations are co-designed. For these reasons, effective planning requires a plan-led approach: spatially, economically and strategically.

#### 4.3 Example of a Plan-led Approach: Guidelines for Inclusive, Low Carbon and Climate Resilient Secondary Cities in Rwanda

The Global Green Growth Institute in Rwanda advocated such an approach, to redirect capital-centred economic growth, to create sustainable secondary city regions instead [35]. They intended to develop a plan that brought together the various infrastructure systems, and considered outcomes in terms of employment, carbon emissions and climate resilience, wider sustainability and inclusiveness – and economic outcomes. The vision developed to inform this plan is set out in Table 2.

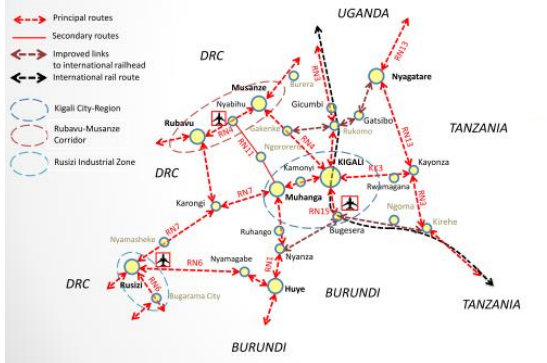
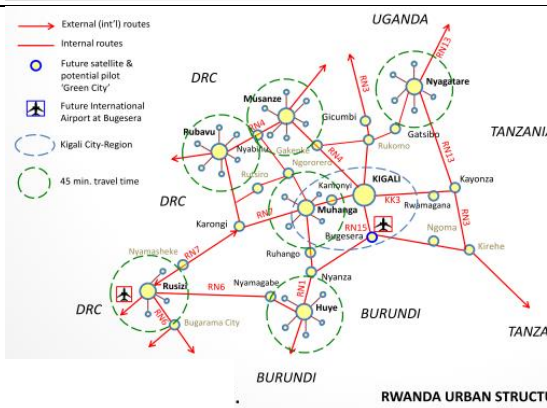
**TABLE 2.** Green City Vision: Inclusive, Low Carbon and Climate Resilient.

Source: Adapted from [36].

<i>Vision Theme</i>	<i>Key Aspects of Guidelines</i>
<b>Green circular (sustainable) economy</b>	Cities and their surrounding regions develop to net zero carbon emissions and sustain a diverse green, locally resilient, full and high quality employment 'circular' economy employing appropriate green technologies; zero waste, sustainable water, material and energy use; secure and resilient local crop production and food supply.
<b>Urban planning and design</b>	Cities as compact continuous grids enabling appropriate density levels and mix of uses. Transit-oriented development accessible for citizens, integrated public transport services, public realm/spaces. Sustainably built and affordable housing in well-planned neighbourhoods.
<b>Sustainable infrastructure</b>	Invest in integrated, sustainable infrastructure to function efficiently locally, linked to their hinterlands and better able to adapt to changing climate/economy
<b>Governance, and skills</b>	Ensure sustainable urban/regional economic development; democratic accountability, engaged citizens, all have access to high quality public services.
<b>Resilience</b>	Cities 'future-proofed' through good environmental planning and management to preserve natural capital, reduce impacts and ensure the long term resilience.

This vision and associated economic and spatial planning guidelines led to two development alternatives being proposed, as set out in Table. 3.

**TABLE 3.** Contrasting visions for green city economies: as growth poles leading to city economies or as sustainable city-regions. Source: Adapted from [36].

<p><b>Crossroads/regional hub scenario.</b></p> <p>Focuses on how secondary cities can develop primarily as hubs of international connectedness, building infrastructure to drive economic growth in Rwanda, attracting inward investment to maximise economic growth in an increasingly globalised world.</p> <p>Assumes intensive effort to improve international/national transport infrastructure with high traffic growth to justify investment.</p>	 <p><b>RWANDA URBAN STRUCTURE</b> "Cross roads/regional hub scenario"</p>
<p><b>City-Region Scenario.</b></p> <p>A higher share of urbanization occurs in smaller settlements within the catchment area of the secondary cities, connected to, and developing alongside, the secondary cities themselves.</p> <p>Focus on improved rural-urban linkages to strengthen the rural (hinterland) economy, through local resource and energy use, assets and building local resilience, not relying heavily on wider investment and commodity exports in increasingly volatile and uncertain world market.</p>	 <p><b>RWANDA URBAN STRUCTURE</b> "City-region scenario"</p>

These two scenarios represent two substantially different development pathways. The choice is between prioritising the resilience of cities primarily in terms of connection to the current dominant economic system (and capital) or to a more localised social and environmental sustainability. The resilience and sustainability of the chosen model of infrastructure investment will depend on whether short-term economic development trumps long-term sustainable, resilient and inclusive outcomes. This choice is reflected in the current widely promoted notion of an infrastructure gap, as discussed below.

#### 4.4 Overall Investment Choice: Prioritising a Resilient, Sustainable and Inclusive Futures requires less (not more) infrastructure.

The current approach to infrastructure development remains one focused on resilience of infrastructure, not sufficiently on infrastructure as part of a resilient pathway to sustainable and resilient futures. This is highlighted by overall targets to address the so-called infrastructure gap and scale up infrastructure investment overall. An example of this conflict is planning in the UK. The UK's National Infrastructure Commission's plan [37] which focuses on the link between infrastructure "gap" and economic growth and presents climate change and climate

resilience as a constraint to this investment, not what it is primarily prioritised for. In contrast, the UK's national 5-year carbon budgets [38] are not applied to planning or infrastructure investment, and increases emissions.

This links back to the initial question of how resilience applies to infrastructure (section 2 above). OECD research [8] set out the need to focus not on the 'climate resilience of infrastructure' but infrastructure for low-carbon and climate resilient development. Their report aims to advise governments how to '*finance their transition to a low-carbon, climate resilient economy*' through a '*unique leapfrogging opportunity to shift those investments towards low-carbon and climate resilient infrastructure*'. It views this as part of the general challenge to address the '*infrastructure financing gap*', but also to shift this towards low-carbon and climate resilient options. Therefore the approach proposed to embed climate resilience at the investment options stage, not through safeguarding/screening type approaches.

There is a need to better integrate these approaches and, through doing so, address the current separation (see ODI [40] and others) between strategic investment plans and national climate strategies, and how they are planned and delivered.

## 5. CONCLUSION

In conclusion, we propose the following:

1. That resilience needs to be considered in context. For example, considering not just the resilience of infrastructure, but what it is for.
2. Resilience must look long-term include climate mitigation, adaptation and wider environmental sustainability. Resilience should also be inclusive.
3. Therefore **Sustainability, Inclusiveness and Resilience** should be considered together. This means considering long-term climate and environmental **risks and opportunities** together.
1. There is a need to look beyond sustainable and resilient solutions and places, **to wider sustainable and resilient local economies and development pathways.**

Therefore, it is vital that urban planning embeds an acceptance that while some climate disasters are inevitable, absolute climate catastrophe is not. And in that space between increasing climate disaster and utter catastrophe, there is space for hope and collective action for us to act. To ensure that disaster is limited, an overall pathway shift is required.

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## 2. CHILD-CENTRED HAZARD, VULNERABILITY AND CAPACITY ASSESSMENT AND PLANNING IN URBAN SETTINGS

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**ABSTRACT.** This paper summarises the work and findings of a research project investigating hazards, vulnerabilities and capacities assessment (HVCA) approaches and toolkits that are currently used to design interventions to reduce children's risks from hazards and disasters in urban settings. The project sought to identify effective methods and approaches, and to provide guidance on how to adapt or develop tools to better identify vulnerable urban children and understand the risks they face. The research comprised analysis of relevant HVCA toolkits, and key informant interviews with practitioners involved in disaster risk reduction, climate change adaptation, child- or youth-centred development, and urban development. New information and communications technologies, and their potential applications to this issue, were also reviewed. The project was commissioned by Save the Children International and is now entering a second phase of piloting an improved method.

**Keywords:** Vulnerability Assessment; Urban Children; Disaster Risk Reduction

### 1. INTRODUCTION

Child-centred disaster risk reduction (DRR) (paying specific attention to children's needs in planning and interventions) and child-led DRR (engaging children in designing, implementing, communicating and advocating for interventions) aim at minimizing disasters' impacts on children and adolescents. DRR strategies that give particular attention to children's needs, skills and perspectives can make significant contributions to their resilience [1-2]. The main international policy for DRR, the Sendai Framework for Disaster Risk Reduction 2015-2030, recognises that 'children and youth are agents of change and should be given the space and modalities to contribute to disaster risk reduction' [3]. This also contributes towards realising children's rights to special assistance and protection, and to their participation in reducing risk [4-5]

Urban children face many different kinds of risk, which are linked to poverty, inequality and discrimination. Research has identified a range of factors influencing their vulnerability and exposure to risks and disasters, their capability and rights to participate in DRR as agents of change, the barriers and opportunities for participation, and their access to protection and services. Marginalized children are at particularly high risk: they include street children, child labourers, and children living in informal and low-income settlements [6-9].

Hazards, vulnerabilities and capacities assessment (HVCA) is a key element in DRR and climate change adaptation (CCA) programming. HVCA is a method of investigation into the risks that people face in their locality, their vulnerability to those risks and their capacity to

cope with and recover from disasters. Its purpose is to: identify groups who are vulnerable; the factors that make them vulnerable and how they are affected; assess their needs and capacities; and ensure that projects, programmes and policies address these needs. HVCA is used as a diagnostic tool, a planning tool and a tool for empowering and mobilising vulnerable people. Many different HVCA frameworks and toolkits have been applied in various contexts and at a range of scales.

Participatory HVCAs, influenced by participatory rural appraisal or participatory learning and action (PRA/PLA) thinking and tools, and used principally by non-governmental organisations (NGOs), other civil society organisations and local actors, have been effective in capturing the experiences and perceptions of vulnerable, marginalised and excluded people, and have played a significant role in their engagement in DRR/CCA processes and empowerment through this involvement [10]. Information and communications technology innovations such as digital mapping, smartphones, mobile internet and cloud computing, together with crowdsourcing and citizen science approaches, have the potential to support and expand traditional participatory data-gathering and analysis [11-13].

HVCA is designed to take a holistic view of risk, considering a wide range of environmental, economic, social, cultural, institutional and political pressures that create vulnerability. In practice, most HVCAs are community-wide assessments and therefore quite broad in scope. Relatively few focus on children's vulnerability and agency or are informed by sound understanding of child protection and wellbeing issues. HVCAs tend to concentrate on risks resulting from environmental or technological hazards (e.g. flood, fire) and pay less attention to other significant or widespread social threats to children (e.g. domestic violence, bullying, exploitation in the labour market). The few HVCA guidelines that do focus on young people vary in their quality and sophistication. Plan International's toolkit on child-centred DRR and Save the Children's guide to child-led DRR do contain detailed guidance on HVCA training and application relating to children and young people, although they do not distinguish towns and cities from other contexts [14-16].

HVCAs should be tailored to the contexts where they are applied and involve participation from those most at risk or traditionally marginalized from decision-making processes. Participation of children and young people should be a central component of child-centred DRR/CCA design and implementation. Children can identify problems, particularly human-induced and societal risks, which adults often overlook or underestimate (e.g. social exclusion, alcohol abuse) [17]. Children's organisations are also good at listening to children's views of hazards and vulnerabilities and giving voice to those views in public arenas [2]. In practice, these contributions are not widespread and are often not acknowledged by local governments and other agencies [18], although Save the Children has considerable experience of this across the world, and has produced a range of practical guidance with examples of good practice [14,19-21]. This is paralleled by child-led or child-friendly assessment tools applied by other organisations in DRR and CCA contexts [16, 22].

Development of HVCA methods and tools for urban applications needs to be informed by sound understanding of the distinctiveness of urban systems, contexts and issues, and the known challenges of carrying out HVCA in urban settings [23-25]. Sophisticated methodologies and toolkits for urban risk and vulnerability assessment, such as the World Bank's Urban Risk Assessment methodology and the Arup/Rockefeller City Resilience Framework and Index, are designed for holistic, system-wide assessment by city

administrations [11, 26]; there are also a number of participatory tools and approaches used to investigate urban risk and for CCA [27]. The extent to which these have been used to identify children's risks, vulnerabilities and capacities is unclear.

## **2. METHODOLOGY**

The research project investigated HVCA approaches and toolkits currently used by practitioners to design interventions to reduce children's risks from hazards and disasters in urban settings. It sought to identify successful approaches and useful methods, and provide guidance on how to adapt or develop better tools to identify vulnerable children and understand the risks they face.

The research, which was commissioned by Save the Children International, comprised a scoping exercise and a needs assessment. The scoping exercise analysed 20 relevant HVCA toolkits, which were identified through literature searches and key informant referrals. The toolkits were designed by a variety of organisations, principally NGOs, and covered a range of contexts. Most addressed communities in general; four were designed to look at urban areas; six were child-centred; and two focused on school settings. The HVCAs also tended to focus on local levels: only two of those examined were designed to analyse factors contributing to risk, vulnerability and capacity building at a wider range of levels, from household to national.

The needs assessment was based on 23 key informant interviews (KIIs) with NGO practitioners involved in DRR, CCA and child- or youth-centred development; practitioners and researchers with experience of developing and testing HVCA tools; and urban development practitioners. The investigation focused on experiences in Asian cities. The initial interviewees were identified by Save the Children, and additional participants through snowball sampling. The interviews, which were mostly conducted by telephone, were semi-structured using the same interview protocol; each interview lasted from 1-2 hours. Interviews were recorded for coding and analysis.

## **3. FINDINGS**

### **3.1 Assessment tools and approaches**

HVCAs are toolkits comprising many different tools or activities. In this sample, the number of tools or activities used in each HVCA toolkit ranged from 5 to 15. Apart from some modifications to fit different contexts, the types of tool did not appear to vary much across the different toolkits and guidelines. This implies a high degree of consensus among the organisations that developed and used them, although the application of specific methods in the field is likely to have been more diverse. The main tools were standard ones used in participatory learning and action: local, community or school mapping (of hazards, resources, capacities), seasonal calendars, historical and disaster timelines, stakeholder mapping, transect walks, key informant interviews, focus group discussions, livelihoods analyses, social mapping and hazard ranking. These would be familiar to most users. KIIs indicated that the key strengths of the different toolkits lay in their sensitivity and adaptability to different

contextual issues, and their role in helping to forge relationships between different stakeholders.

Overall, it appeared that HVCA toolkits do not actively encourage users to reflect upon or question the decisions they make during the assessment process. The extent of information provided to support users in planning and choosing the most effective assessment approach and the specific selection of activities varied greatly. Some toolkits took a prescriptive and linear approach, with a fixed range of tools used in a set order. Such guidelines demonstrated a lack of flexibility regarding the choice, application and modification of individual methods and tools, as well as a lack of awareness of the adaptation and re-evaluation that might be needed to use the tools effectively in urban areas.

Some, more extensive, toolkits such as the IFRC's Vulnerability and Capacity Assessment (VCA) and Save the Children International's recently developed Urban Situational Analysis Tool (USAT), put more emphasis on being flexible and reflective during the assessment process. In both cases, detailed guidelines are provided alongside the toolkit itself regarding the various issues, challenges and discussion points that users should be aware of during assessments. Both documents also provide a level of questioning, engaging users to question their own decision making and the structure of the assessment itself.

### **3.2 Coverage of urban risks**

KIIs believed that more could be done to construct a comprehensive urban HVCA toolkit. Some urban issues were missing from toolkits that had been originally developed for rural areas and then adapted for urban settings. There was little evidence of tools aimed at identifying and assessing risks and vulnerabilities that are more prominent in or specific to urban areas (e.g. road safety, air pollution, exposure to hazardous materials, drug use and trafficking, violence, child trafficking, child labour and risks to children working on the streets). Although urban applications of HVCA are mostly in poor or informal settlements, none of the tools considered the daily risk of eviction and its consequences. It was noted that some toolkits did not recognize children's desire to play, and there seemed to be no tools that sought to recognize where urban children played, the dangers those urban spaces presented, and what other, safer spaces might be available. Street children and child labourers, who are particularly at risk, were mostly identified through the process of implementing projects rather than HVCAs. However, there was evidence of HVCAs directing projects towards focusing on children in particularly difficult situations, such as single migrants, refugees and children in unauthorized settlements. Risks to children from medium- or high-income areas were not identified, even though their geographical location within a city might expose them to certain hazards.

### **3.3 Understanding urban 'communities'**

Defining 'community' in an urban context and understanding how to work in such communities was the barrier most often reported in the KIIs. The initial responses of some interviewees revealed that they did not consider urban areas to have the same sense of community as rural areas seemed to have. Urban communities certainly do exist, but they take forms that may be very different from those in rural locations, and they may not be easy to identify. With this in mind, the challenge is to ensure that project staff understand the different forms of urban communities, how they are created, and how best to reach them through the HVCA process.

Tools developed for application in rural programmes, although familiar to most users, are designed with rural conditions in mind, where communities and their structures are more visible and there are relatively high levels of participation. They may be less useful when trying to identify, differentiate between, or engage with, the diversity of stakeholders and roles, power and decision-making structures, relationships and networks in urban areas.

### **3.4 Risk priorities**

The research team noticed that the key informants said little about CCA or how it can be integrated into HVCA toolkits. On the other hand, some interviewees identified forward thinking as a gap in current assessments: new and emerging risks were not being considered, but in complex urban contexts these should be addressed. Several interviewees suggested that urban communities' lack of awareness of hazard risks was an obstacle to their engagement with DRR initiatives. This view is at odds with some research into risk perception and risk management practices of the urban poor, which presents a more complex and positive picture [28-29]

Nevertheless, environmental hazards may not be seen as a priority by the urban poor; and the conventional project approach to DRR, based on HVCA, may not be the best entry point. In one urban DRR project in India, an initial phase of participatory HVCA focusing on natural hazards failed to engage the interest of community members. The project then shifted the assessment's focus to social protection issues (including access to schools and local governance institutions, and access to food rations) that were a higher priority problem for the community. This shift dramatically increased community engagement, and from this point onwards project staff were able to work with community members to explore links between risk reduction and social protection. One interviewee suggested avoiding compartmentalizing different aspects of hazards, risks and vulnerabilities, as these are often perceived as one interconnected issue at the local level. A comprehensive urban HVCA might therefore need to consider an extensive range of risks, or link to other tools that examine these.

### **3.5 Children's voices**

NGOs working with children and young people aim to provide change from the ground up, by engaging children, families and civil society in securing child rights. When discussing the ways in which their organisations engaged with children, the interviewees described a range of approaches, with different levels of children's involvement. In some programmes, engagement appeared to be strong, although not always age-responsive. In others, the ambition of following participatory approaches that engaged children in consultation about programme design and implementation did not necessarily translate into more substantial involvement in project activities. Voice did not seem to be well ingrained in any of the HVCAs and toolkits discussed with the key informants. Promoting the voices of children and young people appeared to be almost solely reliant on how the programme staff using the toolkit decided to implement it. Moreover, urban children appeared not to be recognized as agents of change in the same way that children in rural areas were: this issue deserves further investigation.

### **3.6 Stakeholders**

HVCA toolkits and methodologies are expected to incorporate a wide range of stakeholder groups into the assessment and DRR programming process (e.g. groups of children, parents of children, other key adults and community members, teachers, NGOs, government officials). This broad perspective is essential for capturing the wide range of often complex issues associated with vulnerability, capacity and building resilience. Nevertheless, engaging so many stakeholders can be a time-consuming and challenging process.

The KIs also raised questions about how to work with informal groups or localised self-governance and draw upon their capacities, recognizing that community-based, informal, governance mechanisms exist in all urban settings and need to be integrated into HVCA. Assessment tools also need to interrogate the underlying motivations of stakeholders who may work (willingly or unwillingly) to keep children in positions of risk and poverty.

### **3.7 Time**

Time constraints were identified as a major barrier to carrying out HVCAs. Community members either do not have the time needed to participate in HVCAs or are not willing to give it. KIs suggested that one reason for their unwillingness was that environmental hazards were not seen as a priority amidst many other pressures. One interviewee thought that members of poor urban communities were becoming tired of researchers and had reached a saturation point in terms of engagement with such processes.

## **4. TECHNOLOGICAL INNOVATION**

A separate component of the project reviewed research and case studies of technological innovations that can support HVCA and child-centred DRR in urban areas [30]. This included technology that can be directly used by participants (e.g. mobile telephone, apps and balloon mapping) and indirectly through analysis of large data collections. Access to the internet and mobile phone technologies has an important role to play in achieving development goals [31]. Many children and young people have access to technologies such as social media, apps and computer games and it would be pragmatic to use technologies that are already available in HVCA. Participatory geographical information systems (PGIS), volunteered geographic information (VGI), mobile technologies and smart phones can be used by at-risk and vulnerable populations [32], for example by migrant children [33-34].

New technologies can be used to detect hazards, identify the exposure and vulnerability of children, and implement risk reduction initiatives; they can also be used as child-centred learning tools. For instance, they have been suggested as a support to sexually abused children, by reducing vulnerability factors such as loneliness and lack of confidence [35]. So-called 'big data' systems that collect and process large volumes of information have been applied to public decision making and action regarding children's welfare [36-37]. Civic science and open hardware can be a catalyst for engaging local communities, including children [38]. Work on 'smart cities', where new technological and computational capabilities are geared towards change and adaptation, offers insights into human behaviour and preferences that can be used for predictive modelling [39-40]. Big data and predictive analysis have been tested in New Zealand to deliver a predictive risk model focusing on children's welfare [41-43].

## 5. CONCLUSIONS

To address the issues and barriers to progress identified in the discussion above, programme staff in development organisations need to be given the freedom to adapt, customize and borrow from existing toolkits to fit them to the specific contexts they are working in. The organisations could support this process by making relevant information available (e.g. an online platform of different tools, toolkits and related resources), providing access to experts for advice (possibly an HVCA focal point or a community of practice) and working in partnerships. Most development organisations' country offices and programmes engage with risks and vulnerabilities in one way or another. In the case of HVCA, there is no need to invent the wheel. Development and testing of new toolkits would be a major task requiring considerable time and resources. Most of the relevant tools, methods and approaches are already in existence, and many field staff are familiar with them; but they can be used more effectively through an iterative process of learning and improvement.

One way of achieving such improvement could be through focusing on the decision-making processes through which HVCA tools and toolkits are selected and deployed. The project team recommended developing a pre-assessment process tool that would enable users to plan and choose their approaches more effectively by making them reflect upon, and question, the decisions they make during an HVCAP (HVCA and Planning) process. This integrative approach could be applied to many different tools or toolkits and operational contexts. It would ensure that everyone within an organization goes through the same robust, deliberative decision-making process for planning individual HVCAPs and implementing projects based on their findings, while allowing for flexibility regarding the choice, application and modification of individual methods and tools. No toolkits currently contain such a process tool, but a recently developed pilot version [44] is currently being tested by Save the Children International as a follow-up to the project described in this paper.

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### 3. USING RURAL POST-DISASTER RECOVERY EXPERIENCES TO REFLECT ON RESEARCH OPPORTUNITIES FOR UNDERSTANDING SELF-RECOVERY IN URBAN ENVIRONMENTS

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**ABSTRACT.** The majority of families in developing countries recover from disasters by making use of their own resources, knowledge and initiative: in other words, they self-recover. Yet the process of self-recovery is poorly understood and there is a lack of knowledge and evidence on how to support it. This paper builds on the knowledge gathered throughout an inter-disciplinary pilot research project between four collaborating partners, British Geological Society (BGS), the Overseas Development Institute (ODI), University College London and CARE International UK. It examines self-recovery processes in rural and some peri-urban environments affected by rapid-onset disasters in the Philippines (typhoons Haiyan (2013) and Haima (2016)) and Nepal (Gorkha earthquake 2015). The discussion draws on emerging themes about self-recovery in rural environments and reflects on how these themes may compare when addressing self-recovery in urban environments. Building on this reflection, the paper highlights the persisting gaps in knowledge and how different disciplines and stakeholders might collaborate in further research to better understand how to support self-recovery within urban environments.

**Keywords:** Recovery, self-recovery, shelter, humanitarian response, disasters, rural, urban, strategies, communication

#### 1. INTRODUCTION

The last decade has seen the term ‘self-recovery’ increasingly used to refer to the process whereby individuals and communities affected by disasters reconstruct their houses using their own resources, knowledge and initiative [1]. It is estimated that humanitarian agencies struggle to meet as much as 30% of the shelter needs within the first 12 months of a disaster; in many cases this percentage is significantly lower. In cyclones Sidr (Bangladesh 2007) and Nargis (Myanmar 2008), only 1% and 2.5% respectively of the total shelter need was met [2]. The other households self-recovered in one way or another, but very little is known about the process in both rural and urban post-disaster environments. Existing knowledge comes mostly from humanitarian agencies’ evaluation reports relating only to known beneficiaries of agency assistance to self-recovery activities, rather than the affected population as a whole [3-5]. This is largely because self-recovering communities tend to be isolated geographically, socially or politically and are therefore difficult to access; or because they do not fall within the beneficiary selection processes of humanitarian organisations [6-8].

The term ‘self-recovery’ is applied mostly to shelter reconstruction. The term can be misleading because it might suggest no input from any other actor, not only national and international level actors but also localised bonding social capital networks including friends,

family, and neighbours – which is unlikely in any post-disaster situation. Its relation to the shelter sector can also be misleading because it risks over-simplifying what is a very complex and multi-dimensional social practice that moves beyond the built environment. Recovery is a subjective and organic process. It incorporates aspects such as basic needs, shelter, health, livelihoods, protection, security, education and culture recovery. Each of these has different and shifting levels of importance. The overall pace of recovery is determined by a range of factors including the scale of the event and the social, environmental, political and economic contexts in which recovery takes place [9]. Nevertheless, housing reconstruction is central to recovery, often acting as a ‘crude surrogate’ for many other aspects of economic and societal recovery, such as safety, local administration, schooling, healthcare, water and sanitation and livelihoods [10]. What is more in theory, the shelter sector identifies disaster affected individuals as the first and most central actors in recovery processes. The use of the concept is intended to reflect that, irrespective of the potential involvement of other actors [11-12].

This paper examines self-recovery processes in peri-urban and rural environments affected by rapid-onset disasters in the Philippines (typhoons Haiyan (2013) and Haima (2016)) and Nepal (Gorkha earthquake 2015). Urban populations are increasingly exposed to climate and non-climate related hazards leading to disasters [13]. Yet, although humanitarian responses have demonstrated the difficulties of achieving efficiency, efficacy and timeliness within urban environments [14], research on self-recovery in urban environments is limited. Existing research relates to urban responses more generally, is ‘self-referential’ and completed within a limited timeframe [15]. This provides little space for alternative and innovative thinking by learning from other sectors, about how to improve humanitarian responses within urban contexts. At this stage, this paper can therefore only reflect on what the existing research has found about self-recovery in rural areas and propose emerging themes as potential directions for additional research. This can motivate discussion and possible collaboration between multiple disciplines and sectors to make humanitarian practice more relevant, timely and accountable to those that self-recover in post-disaster urban contexts.

## **2. METHODOLOGY**

To capture the complexity of self-recovery, an inter-disciplinary research team was assembled comprising specialists in the environmental (British Geological Society) and social sciences (Overseas Development Institute), structural engineering (University College London) and humanitarian shelter practice (CARE International UK). The social scientists engaged with families and local builders to better understand local knowledge systems and the wider range of factors that influence decision making processes. The engineers and humanitarian shelter practitioners evaluated housing structures and construction processes. The environmental scientists assessed risks to housing from the local environment. Their work was carried out in parallel, working in the same research locations. This enabled the team to study the same case through the different disciplinary lenses. The approach provided explanatory power in a range of areas, for example, regarding the reasons why people rebuild in unsafe locations and levels of household uptake of technical guidance on safer building.

The team adopted a mixed-methods, case study methodology (see table 1)<sup>5</sup>. The qualitative element of the research was a combination of transect walks, semi-structured interviews and focus groups. Transect walks, guided by local community leaders and/or social mobilisers, allowed for the collection of visual data and community perceptions relating to the physical landscape and local hazards, housing typologies, the state of reconstruction, land use and settlement location. Semi-structured interviews carried out with a range of community members including homeowners, local leaders, builders and carpenters allowed for the team to gather data relating to individual and household recovery experiences. This included experiences before, during and after the disaster, information on recovery decisions and pathways, reconstruction choices and factors such as household risk perception and opinions and expectations of external assistance. Focus groups explored the strategies adopted by communities to prepare for and recover from the disasters, the factors that influenced their vulnerability (e.g. landslides, increased market prices, droughts, changing weather patterns, road clearance and improvement) and the role that local institutions, authorities and families played in supporting recovery.

The quantitative element consisted of building surveys which recorded data on the households' experience with the hazard (e.g. direction of the wind, direction of the shaking, behaviour of the building), building typology (e.g. vernacular or not), and structural details including the incorporation of techniques for safer building and hazard mapping using GPS devices addressing other hazards (e.g. flooding, drought, landslides) in the area that have impacted the recovery processes. The methods complemented each other, providing a holistic and detailed idea of people's self-recovery processes. The qualitative investigation added people's voices and experiences to the data gathered in the surveys, while the surveys provided specific examples of reconstruction practices and assessments of the environmental contexts in which their recovery was taking place.

**TABLE 1.** Research methods in each country

Country	Date visited	# Transect walks	# FGDs	# Interviews	# Survey forms
Philippines	3/06/2017 - 3/17/2017	14	35	21	36
Nepal	4/22/2017 - 5/01/2017	13	20	21	11

In the Philippines the research team visited 14 rural and peri-urban *barangays*<sup>6</sup> of which six were on Leyte island (affected by Typhoon Haiyan in 2013) and a further eight on Luzon island (affected by Typhoon Haima in 2016). The areas visited varied in natural landscape, accessibility and soil typology. Most were accessible within two to three hours from a main town except two that were accessible within a four-hour car ride and a two-hour hike. All of the *barangays* were home to beneficiaries of CARE shelter and/or livelihoods assistance provided by local implementing partner organisations, although not all community members had been selected as beneficiaries. In Nepal the research team visited 11 village development

<sup>5</sup> For a more detailed discussion on the interdisciplinary methods and methodology adopted see Twigg et al. 2017: <https://www.odi.org/publications/10963-self-recovery-disasters-interdisciplinary-perspective>

<sup>6</sup> A *barangay* is the smallest administrative division in the Philippines; the term is used by Filipinos to mean a village, district or ward.

committees<sup>7</sup> (VDCs) in Dhading district. Between one and three communities were visited in each VDC. Dhading is characterised by highly mountainous landscape with river valleys. The VDCs visited were chosen based on their varied soil and rock types as well as their accessibility. Accessibility of these communities varied between a three-hour car ride to a four-hour hike.

### 3. SELF-RECOVERY PROCESSES

#### 3.1 Philippines

Typhoon Haiyan, known locally as Yolanda, impacted the Philippines on the 8<sup>th</sup> of November 2013. One of the strongest typhoons to ever make landfall, Haiyan caused widespread destruction, particularly across the Visayas region. More than 14 million people were affected, more than 4 million displaced and over 6,000 were killed; 1.1 million houses were damaged of which more than half were destroyed completely [16]. The impact of the event quickly outpaced the government's capacity to respond effectively, leading to its call for international humanitarian assistance.

These experiences contrasted with those associated with typhoon Haima, known locally as Lawin, which made landfall on the 19<sup>th</sup> of October 2016. Haima also caused serious damage to homes and livelihoods, particularly, across the Cagayan and Apayao provinces of the Northern Luzon region. At least 15 deaths were attributed to Haima [17], the typhoon displaced around 200,000 people and damaged or completely destroyed almost as many houses [18]. Despite the high impact, the government led the humanitarian response and declined offers of international assistance

Following both disasters, shelter construction and reconstruction was a priority for affected families. They took steps to recover their shelter immediately, mostly by salvaging and reusing (or in some cases buying new) materials [19]. Many households had reconstructed a shelter before external assistance arrived. In some cases, what had originally started as an entire temporary shelter formed one part of a larger, more permanent structure. The research team's visual observations and building surveys demonstrated that people who had already constructed a shelter before new materials arrived, subsequently used these to build shelters for their livestock or expand shelter size rather than replacing the old materials on their house. Livestock is an important source of livelihood for rural families and often cited as an immediate priority for households once their basic shelter needs had been met. Some households that had rapidly reconstructed found themselves ineligible for shelter assistance by the time assessments for beneficiary selection were carried out, on the basis that, their houses were believed not to have been damaged by the event.

Many communities relied on community organization underpinned by traditional systems of *bayanihan* for household reconstruction. *Bayanihan* is central to Filipino culture: it refers to feelings of concern for the community, and the taking on of other people's burdens [20]. In practice this translated into community members grouping together to build shelters for neighbours, often starting with the most vulnerable individuals in their community. However, while *bayanihan* was often celebrated by communities there was, at times, the suggestion that

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<sup>7</sup> A Village Development Committee (VDC) is the lower administrative division of the Ministry of Federal Affairs and Local Development. VDCs function in a similar way to municipalities but with greater levels of interaction and administration between the public and the government.

wealth and power imbalances meant that some people benefited from the process more than others. While local official leaders known as *barangay* captains played an important role in recovery by acting as the bridge between the municipal governments and affected communities, Filipino dynasties, geographical accessibility and nepotism were frequently referenced during interview conversations on abilities to recover at individual, household and community levels.

Beyond affected individuals and communities, a number of other actors influenced strategic choices in recovery (e.g. whether or not to relocate; what materials to use in reconstruction; changes to livelihood strategies) as well as the speed of interventions and beneficiary selection processes. Other actors, for example, religious, family and neighbourhood networks were clearly relevant in shaping pathways of recovery. Individuals often referred to family members that were Overseas Filipino Workers (OFWs), a main source of income for the country and an important economic asset for households<sup>8</sup>.

Shelter actors aimed to support people in building a safer, permanent house [21-22] using a 'self-recovery' approach that is operationalised using financial (cash and/or voucher provision), material (provision of materials and tools for construction as well as support for salvaging and reusing debris) and/or technical assistance (provision of guidance on construction through training and/or guidelines and mass communications). The technical assistance focused on communicating and promoting Build Back Safer (BBS) messages<sup>9</sup>. Similarly, actors supporting livelihood recovery also used a three-pronged approach aiming to reboot local economies and complement the shelter interventions. However, although people's agency in reconstruction was impressive, their frequent use of low-quality materials was a concern as this can be at the core of either mitigating or reinforcing vulnerabilities [23]. Poorly constructed, unsafe buildings are frequently the largest cause of serious injury, trauma and death when a disaster occurs.

### 3.2 Nepal

On the 25<sup>th</sup> April 2015, a 7.6 magnitude impacted Nepal with the epicentre in Gorkha district. Gorkha borders the Dhading district province where this research was carried out, which lies around 76 kilometres from the capital Kathmandu. The earthquake had a devastating impact on housing stock, destroying more than 600,000 houses and leaving almost 300,000 partially damaged. The event affected more than 8 million people, displaced around 117,000 and caused injury to more than 22,000 [24].

The self-recovery experiences of disaster affected communities in Nepal contrasted significantly with those in the Philippines for several reasons. A range of environmental factors in the weeks and months following the event seriously challenged initial self-recovery efforts. Some reports have stated that the main earthquake was followed by more than 300

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<sup>8</sup> See Philippine Statistics Authority: <https://psa.gov.ph/content/statistical-tables-overseas-filipino-workers-ofw-2016> & ILO 2008 [http://www.ilo.org/wcmsp5/groups/public/---asia/---ro-bangkok/documents/publication/wcms\\_160579.pdf](http://www.ilo.org/wcmsp5/groups/public/---asia/---ro-bangkok/documents/publication/wcms_160579.pdf)

<sup>9</sup> Build Back Safer (BBS) messages were developed through a consultative process with shelter agencies and government as a part of the Typhoon Haiyan / Yolanda response in the Philippines and can be seen as a minimum checklist of disaster risk reduction construction techniques for owner-driven self-recovery in non-engineered, non-architecturally designed lightweight structures that most shelter agencies were dealing with. BBS messages are often developed as part of shelter responses to different disaster contexts [26].

aftershocks including another 6.7 magnitude earthquake on April 26<sup>th</sup> [25]. The scale of the event and the aftershocks increased the level of fear that people felt in relation to the environment owing to the potential for rock fall, landslides, further building collapse and the unpredictability of earthquakes.

While in the Philippines people made attempts to start clearing debris for reconstruction relatively soon after the event, in Nepal people were often both unable and unwilling to return from nearby displacement camps to previous settlements to carry this out. Many communities described this as a key strategy in early recovery, building communal shelters and living together for several months after the initial shock. This enabled people to meet their immediate priorities of food and shelter in the aftermath of the earthquake, but also ensured they had the time to overcome the feeling of fear, which resonated every time they experienced an aftershock or trembling from a nearby landslide.

Additionally the monsoon period that lasts from June and to September served to further delay self-recovery efforts with the heavy rains making debris clearance and reconstruction impossible and significantly increasing cases of illness. Recovery and reconstruction in the rural and mountainous areas was also disrupted by the damage to local transport and infrastructure links caused by the earthquake and subsequent landslides. This restricted access and the flow of materials for reconstruction but also increased the costs associated with their transportation and caused feelings of isolation. In view of these challenges, communities often discussed their mobilization for fixing roads and removing debris from landslides. Furthermore, people discussed their seasonal, temporary or permanent movement to other areas less isolated from their villages, particularly during the monsoon season.

Many households had been unable to reconstruct at all and remained in temporary shelters. Families with irregular land tenure were not eligible to receive government financial assistance, which posed a significant challenge to their recovery. These groups, often the most vulnerable, included those living on religious *guthi* land, families living for years on government land or marginal land, and grown-up offspring who had built houses on their parents' property but did not have separate title. The inability of these households to access assistance meant that those who had managed to rebuild a shelter had gone into high levels of indebtedness through reliance on bank loans, credit cooperatives or money lenders, and had reconstructed houses that were no more earthquake-resilient or safer than their pre-disaster condition.

Overall, the event rapidly overwhelmed the capacity of the government to respond, resulting in their call for international assistance. The NGO shelter response then focused mainly on the distribution of materials and tools, technical assistance and training (for local carpenters, plumbers and masons), followed by cash grants, winterisation and housing design [27].

That said, the government is continuing to play a heavily centralised role in the reconstruction of the affected districts and has placed much of its focus for recovery on owner-driven housing reconstruction. The National Reconstruction Authority (NRA) and Housing Recovery and Reconstruction Platform (HRRP) have developed several housing typologies and made financial support for reconstruction conditional on the incorporation of structural features to increase earthquake resilience [28].



Recovery in Nepal has, however, been stalled by lengthy delays in distributing cash for reconstruction, as well as a shortage of trained engineers to provide information, advice and guidance to households throughout the reconstruction process. Interviewees often explained that they felt unsure as to whether their housing was structurally safer or not and whether they had met the conditions to receive subsequent tranches of funding. As a consequence, families felt they were unable to re-establish the type of emotional feelings of safety in the home that are important for psychosocial recovery from the event [29].

Furthermore, research findings indicate a discord between government and community perceptions of the aim of the financial assistance that was being provided. The government maintained that the assistance was a support to recovery that households should then top up using their own resources; and some households had indeed managed to do so by making use of their access to overseas remittances or through loans and relying on labour exchange with other community members. However many households saw an unbridgeable shortfall between the cash grant and the cost of a finished house that complied with the required typologies and techniques.

### **3.3 Emerging themes on self-recovery**

Affected communities in both the Philippines and Nepal demonstrated a capacity to initiate their own recovery through various strategies, whether influenced or not by other stakeholder assistance. Whether it was *bayanihan* in the Philippines or living collectively for a period of time in Nepal, community organisation and the use of social capital were part of people's immediate recovery strategies. The (re-)use of pre-existing resources such as salvaged materials or what was left of their homes and livestock shelters was also identified as a self-recovery strategy. However these actions were heavily burdened by lack of other resources due to debts, insecure land tenure and damaged livelihoods from recurring hazards. Recovery is further burdened by damaged infrastructures and as a result the physical and psychosocial isolation of communities. Furthermore, prioritising their livelihood, diversifying their economic activities and using their human capital were also important steps towards recovery. People's livelihoods emerged as a significant motivation in self-recovery efforts.

The research also identifies themes that present themselves as challenges in supporting self-recovery in practice. One challenge relates to the role that different stakeholders take on as assistance providers and how these roles influence and define recovery pathways by either supporting or inhibiting them. A second challenge relates to the accessibility to adequate and accurate information from those who are recovering - but also those who design assistance – to make informed decisions on how to recover or support recovery.

## **4. SELF-RECOVERY IN THE URBAN ENVIRONMENT**

### **4.1 Implications and persisting knowledge gaps**

Drawing on the emerging themes highlighted from the initial research and applying an urban lens one can propose certain implications for research on self-recovery in urban environments. By identifying knowledge gaps, the following section suggests certain directions for future inter-disciplinary and multi-stakeholder collaboration for supporting post-disaster self-recovery in urban contexts.

#### **4.1.1 Whose recovery?**

Although disaster-impacted individuals are the owners of their own self-recovery pathways, it is a process that is also influenced by the actions of other local, national and international actors as well as the differential power dynamics that operate between them. The influence of these factors on self-recovery is likely to be intensified as urban settings host a greater quantity and wider range of stakeholders. Not only are there more actors, but they also vary significantly in type and often have overlapping relationships that can be difficult to identify and isolate. Urban environments have introduced new forms of both formal and informal stakeholders into the crisis response equation. These environments are also highly dependent on dense economic systems that define market relationships that are not geographically isolated, are very fluid and sensitive to the smallest changes. The understanding of the direction and type of connections between these different actors is very blurred, particularly during emergencies when there is limited time to do so. Understanding these connections is crucial when addressing the kind of support needed for self-recovery and the channels through which it is provided.

#### **4.1.2 Social organisation**

Support mechanisms and networks are not only spatial - within a neighbourhood or around a crossroads - but also virtual, through social media or specific interest groups. The multitude of spatial, virtual, cultural and religious relations within urban environments also diversify the natures of 'communities' within urban environments. Thus, strategies to self-recover through communal action may also change. Communities in rural Philippines often relied heavily on local social structures and *bayanihan* processes for reconstruction, and those in Nepal on the exchange of labour between community members. In densely populated or highly mobile urban environments the type of social cohesion necessary to allow collaborative strategies to take place may differ or not exist at all. Different forms of social cohesion will exist [30, 32, 33]. It is also possible that affected urban communities will rely heavily on international support networks or communities through social media and the internet for example. However when network infrastructures are disrupted in the aftermath of a disaster, the level of support such communities can provide may be considerably limited. The immediate aftermath of a disaster may force new communities to form around common – and urgent – needs [33, 34], although they may only exist temporarily.

#### **4.1.3 Shelter**

Immediate shelter from harsh weather and aftershocks will also be a priority for people in post-disaster urban environments. However, whilst both case studies demonstrate people's initiative and drive to salvage materials and rebuild temporary shelters, the nature, components and space for the reconstruction and repair of shelters will vary considerably in urban environments; if people take part in rebuilding at all. Co-habiting and renting will diversify the already varied typologies of housing and the policies and codes within densely populated spaces will increase the complexity of shelter support. These differences present important implications for urban emergency shelter support for self-recovery and, require further research.

#### **4.1.4 Land tenure**

Both the Philippines and Nepal experiences showed self-recovery to be heavily shaped by issues of land tenure. Not only does land tenure dictate where people can legally reconstruct following a disaster, but it also influences the type and quantities of assistance that they are able to receive from other actors to do so. Land tenure issues are particularly pertinent within low-income urban settlements that are often characterised by complex and insecure ownership agreements that can paralyze response [33]. These locations can quickly come to be declared as no-build zones in the aftermath of a disaster and/or become the focus of resettlement programmes as witnessed following Typhoon Haiyan in the city of Tacloban [34]. Families in such situations are likely to face a series of difficult decisions when self-recovering. In both the Philippines and Nepal people often found themselves making trade-offs between relocation at the potential cost of local social networks and proximities to livelihood-earning opportunities, or returning to old sites and risking reconstruction but potentially with little to no support from governmental or international actors in doing so. In Nepal, people frequently made reference to the relocation of family members to cities or overseas in search of economic opportunities with which they could support their recovery financially.

#### **4.1.5 Livelihoods**

Livelihoods will always be a priority for recovery. However, the strategies and nature of livelihoods vary significantly in an urban environment. How these livelihood strategies may vary further or, perhaps, become more similar to those of rural environments during a crisis will present an interesting question. Such livelihoods may depend on the extent of damage to the urban economy and investment required to reboot it, as well as become subject to the risk of reactivated and/or new forms of crime and violence, particularly within resource-poor, marginalised and informal settlements. How these processes shape, hinder or activate recovery pathways should be a key concern for further research.

#### **4.1.6 Infrastructure, planning and scale**

Land tenure, rental markets, shelter and service provision are key concerns in recovery and longer-term resilience within urban environments [36,37]. Access to functioning services, infrastructure and transport links, although often lacking, was considered to be a fundamental aspect of recovery in rural Philippines and Nepal. People living in urban environments are no less reliant on these services, often being accustomed to functioning infrastructure before the disaster. The heavy reliance on these systems suggests they should be a key priority for local governments in the immediate aftermath of disasters. However, the same reliance will also be a challenge, as cities depend on heavier, more widespread and complex mechanisms that need to be restored. Nonetheless, because urban centres depend so drastically on dense interconnected infrastructural systems [38,39], the investment made to reboot them in the aftermath of a disaster could have highly beneficial consequences for those self-recovering in urban environments.

The issue of infrastructure is inherently connected to that of urban planning. There is a practical gap between supporting self-recovery and the impact of this approach on the wider urban planning and systemic challenges within urban environments [40]. Nonetheless, the implications of self-recovery strategies used by communities – such as moving back into no-build zones - can influence the longer-term sustainability, resilience and preparedness of cities

in the face of future crises. Thus, the challenge and humanitarian knowledge gap lies in understanding how to reconcile the drive to support self-recovery of individuals in crisis-affected urban environments with the longer-term implications of this support that lies beyond the humanitarian mandate. Furthermore, working in urban environments makes engagement with urban planning mechanisms and processes at different scales - as well as the politics that underlie these processes – inevitable and important.

Supporting family and community self-recovery implies working at the scale of individual households and neighbourhoods. However, such practice within urban environments cannot be isolated from engaging with other scales in the city. The more that humanitarians become part of urban crisis response to individuals, the better they will need to understand the parameters in which to work and their impact and role as intervenors in already significantly complex urban systems with multiple scales.

## **4.2 Directions for future inter-disciplinary and multi-stakeholder collaboration**

Complex urban contexts require that those intervening gain an interdisciplinary understanding of the reality on the ground. Most research on urban crisis and humanitarian response has failed to look across sectors (such as shelter, health, water and sanitation, education). [41]. There is a need to not only work across sectors within humanitarian practice but also across different disciplines, actors and scales in the urban setting.

### **4.2.1 Informed intervention design**

The present research provides evidence that decisions made in the early stages of recovery by those who are self-recovering and those who design emergency interventions and select beneficiaries can have significant consequences in the longer term; for example, when temporary shelters are immediately rebuilt by affected individuals who then become ineligible for shelter assistance, demonstrated in the Philippines and Nepal. They have risked rebuilding houses that are reproducing structural vulnerabilities to future events and, by doing so, may not receive newer, higher-quality materials and technical assistance in reconstruction. Ironically, their agency and initiative to take control places them at a disadvantage. Similarly, in urban contexts, those who exercise agency and initiative and find solutions quickly may fall off the radar of humanitarian assistance by living with extended families or rebuilding in light materials within areas more difficult for humanitarian assistance to reach.

Addressing the design of recovery interventions and implementation processes from an informed interdisciplinary and multi-sector approach could support self-recovery pathways and in some cases avoid deferring or inhibiting them. The Nepal reconstruction assistance prioritised safety over other potentially important economic, social and cultural considerations. Traditional Nepalese homes often have shops and tea-houses on the ground floor with living spaces above. A typical mountain house can have a stable for livestock on the ground floor, living space above and food storage in the roof space. Yet three-storey buildings and the wide openings of the traditional shops are outside the provisions of the existing government housing design catalogues. Deviation from these would require additional engineering design, which is largely unattainable for the affected households<sup>10</sup>. The outcomes of the research suggest

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<sup>10</sup> Although field-based NRA engineers were available to respond to cases where additional engineering advice was needed, interviews and observations suggest the vast quantity of requests has overwhelmed the capacity of the engineers based in each VDC.

that this approach, although it supports an owner-driven-reconstruction model, has the potential to disrupt the restoration of family livelihoods and the local economy. Similar risks will present themselves in urban environments where complex land tenures, limited space and multiple livelihood options require increased flexibility in reconstruction processes: a requirement that is very difficult to achieve in face of strict building codes and other legal frameworks, and the increased cost of space.

The significant diversity, of needs, capacities and self-recovery strategies within rural environments becomes more diverse, dense and at a greater scale in urban environments. The body of theoretical knowledge about mechanisms for quickly understanding this multitude of needs, capacities and strategies in post-disaster urban contexts continues to grow [42]. However, evidence suggests that in practice, humanitarians continue to struggle in quickly understanding post-disaster complex urban environments. Nonetheless, the existing capacities of disaster-affected communities in recovery play a significant part in their rate and possible 'success' of recovery and are therefore central to understanding what assistance is most appropriate and why. Yet, the focus of disaster responders is often on the 'how to' question rather than the 'why' [43]. Disciplines should push to work with disaster-affected communities to better understand the contexts in which recovery strategies are shaped, critically engaging with the question of 'why'. Often within the time and resource constraints of emergency and recovery contexts, decisions are made without critically reflecting on their consequences: such as whether or not the assistance is supporting or hindering the recovery and resilience building processes of disaster-affected individuals. Not only are there significant knowledge gaps for those designing humanitarian response but also for those who are making choices to self-recover. In both the Philippines and Nepal, individuals explained that their concerns were not only about making decisions in relation to recovery, but also about being confident that they were making the right one thereafter. Communities often voiced a desire to gain better understanding of natural hazards, changing markets and existing policies that could facilitate and better inform their decisions. Interviewees demonstrated their capacity to make decisions in every aspect - shelter, livelihoods, where to relocate to, what to do with the assistance they received – but suggested the quality and relevance of information at hand to inform these decisions was limited.

#### **4.2.2 Developing effective and efficient knowledge exchange mechanisms**

In both countries, providing technical information about reconstruction was a significant element of the recovery response through the use of BBS messages. However, the application of BBS messages in reconstruction, the misunderstandings of the role of financial assistance and the desire for longer-term accompaniment indicated a gap in access to clearer, more relevant and accurate information. This calls existing information, communication and education (IEC) mechanisms and materials, used in the responses, into question and sheds light on the significant challenge of communication for humanitarian practice in urban environments [44]. Information can spread quickly and in an uncontrolled manner. There can be a large number of stakeholders and sources that can influence or produce information and control access to it. . A good understanding of market and political processes, housing, land and property (HLP) systems, as well as the impacts of hazards on urban infrastructural systems could be particularly valuable to those struggling to recover from urban disasters.

Access to information, communication and empowerment in information management and decision-making should a subject for further research into the use of science, technology and

communication for disaster-affected communities that are self-recovering. Increased efficiency and effective use of IEC materials, as well as more innovative data collection and communication technologies (e.g. GPS, drones, tablets) could significantly improve humanitarian practice in supporting self-recovery in contexts of urban crises.

## 5. CONCLUSIONS

Self-recovery is a new and little understood area of research but is nonetheless gaining increased attention in academic and humanitarian shelter practice circles. What is increasingly evidenced is that it does not take place in a linear and logical way as it is a subjective experience and process. It takes on different forms and priorities that often overlap. Shelter frequently comes hand in hand with livelihood priorities, for example. It is also clear that people make choices and take initiative to recover within hours of a disaster. Evidence suggests that if disaster-affected communities have agency and will adapt assistance to meet their own needs in the way they trust is best, then humanitarian practice and response needs to be more adaptive toward this agency. If it is not, it is likely to inhibit recovery processes.

Although the findings from this paper are based on a rural study, they provide significant direction for further research into self-recovery in urban environments. The paper highlights the inevitability of affected individuals taking action and using their own resources to recover in post-disaster contexts, whether assistance reaches them or not; and therefore, the importance of understanding these processes as they define recovery pathways, long-term resilience, preparedness and vulnerability to future events within urban environments.

Urban environments present fast-paced, dense and complex contexts. Depth in understanding of the multiple systems at play is key to generating better informed humanitarian intervention designs. However, this is only possible by continuing to develop more effective and efficient knowledge exchange mechanisms for inter-disciplinary and multi-sector collaboration. The promotion of safer reconstruction as well as more informed decision-making processes regarding the built and natural environments and risks that people are exposed to depends greatly on stakeholders' ability to effectively exchange information and learn from each other, to generate behaviour changes not only among crisis-affected communities but also of all stakeholders involved in recovery processes.

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## 4. INFRASTRUCTURE INTERDEPENDENCIES: OPPORTUNITIES FROM COMPLEXITY

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**ABSTRACT.** Infrastructure networks such as those for energy, transportation and telecommunication perform critical functions for societal well-being. Recent sociotechnological development has replaced the historical isolation of these systems with unprecedented interdependency. Infrastructure now functions as a ‘system-of-systems’, exhibiting complex and unpredictable behaviour. Consequently, a majority of research efforts into infrastructure interdependencies have focused on risk and vulnerability. Here we explore how these interdependencies can conversely represent opportunities to increase resilience and sustainability. We present a typology for classifying positive interdependencies, and draw on fundamental principles in ecology where complexity is seen to enhance rather than degrade stability. We argue that identifying the nature of opportunities facilitates their adoption and enables better understanding of infrastructure complexity, which in turn allows it to be turned to our advantage. Integrative thinking is necessary not only for mitigating risks to system stability, but also for identifying innovations that make human-created systems more sustainable and resilient.

**Keywords:** Infrastructure interdependency; Complexity; System-of-systems; Resilience; Sustainability

### 1. INTRODUCTION

Infrastructure systems such as those concerned with water, energy and transportation networks perform functions critical to the health and well-being of society by facilitating essential flows of resources, services, and information [1]. Historically, such systems have largely been developed and maintained in isolation from one another, evolving over decades or centuries in many cases as either public or private enterprises. Modern technologies and demands, however, have given rise to an unprecedented degree of complexity and interlinking between previously disparate networks. Infrastructure now functions as a ‘system of systems’, exhibiting complex adaptive behaviour and numerous interdependencies that can leave critical functions highly vulnerable to disturbances, particularly through exacerbating effects of this complexity such as cascade failure [1–3].

As a consequence of this, a majority of research efforts on infrastructure interdependencies have been concerned with risk and vulnerability, placing a primary focus on system complexity

as a negative. Broad challenges emerging from global climate change and population growth are forcing industries, governments and other decision-makers to adapt by reaching across conventional boundaries to share ideas and approaches in order to build resilience in the face of universal concerns [4–6]. Related to this, understanding the interdependencies that have become fundamental to our infrastructure systems is essential if such systems are to be designed, managed, and adapted in ways that will be resilient to future disturbances [2]. Further, an evidence gap has been identified around the need for new models and methods to understand the interdependencies present in infrastructure systems [7–9].

Although risk identification and mitigation make up the majority of research efforts on infrastructure interdependencies, the systematic view that is necessary for such efforts can shed light on beneficial elements of these interdependencies as well. Examples exist where interdependencies have been exploited or proposed to enhance the delivery of essential services, or synergised to create entirely new services [10–12], and climate change adaptation efforts frequently state the need for interdisciplinary collaboration [4, 6]. Where this has been done in practice, however, there has rarely been an explicit recognition of the positive role played by interdependency; yet in complex natural systems it is generally accepted that interdependency and complexity play key roles in enhancing the sustainability and resilience of the overall system [13].

The aim of this paper is to illustrate and discuss the ways in which interdependencies in complex infrastructure systems may be viewed as opportunities for enhancing function, resilience and sustainability. To this end, we propose a threefold typology for considering beneficial interdependencies based on their relative level of integration. Key principles of ecological systems are then discussed, as these represent systems whose complexity builds resilience rather than impedes it, and finally parallels are explored whereby infrastructure systems might learn from the behaviours and structures of natural systems in order to function more effectively.

## 2. INFRASTRUCTURE INTERDEPENDENCIES

Many infrastructure systems have historically been developed in relative isolation from one another, driven by public interests to provide essential services or by private interests to forward a business case. Technological advancements, societal demand changes and evolving external drivers such as climate change and geopolitics have converged over time to drive adaptations in the purpose and behaviour of critical infrastructures. These systems have now grown interconnected and interdependent, forming a global ‘system of systems’ whose functionality is critical to the smooth functioning of society.

In a seminal work that has underpinned interdependency research since, Rinaldi et al. [1] defined *dependency* as a one-way linkage or flow of causality; whereas *interdependency* was used specifically for bidirectional relationships where two separate systems or nodes both exert influence on the other. The authors further proposed a typology for categorising infrastructure interdependencies according to their nature, which has subsequently been widely adopted by researchers. The framework consists of: physical linkages (where systems share a direct material connection), cyber linkages (where system state depends on information flow), geographic linkages (where systems are connected by spatial proximity)

and logical linkages (where systems are interconnected in some other fashion). The existence of this typology has been beneficial in efforts to explore infrastructure interdependencies, as it provides a structured framework by which complex interconnections can be classified, understood and analysed [14–16]. More recent efforts by Carhart and Rosenberg [17] have sought to expand upon the Rinaldi framework, proposing subdivisions to the category of logical linkages such as policy/procedural, societal, and economic interdependencies, as well as describing a framework of twelve variables by which interdependencies may be explicitly described and typified.

Given the critical nature of infrastructure systems, coupled with the uncertainties associated with complexity, the focus of most research on infrastructure interdependencies has been on the risks and vulnerabilities they represent. Infrastructure systems have largely been developed from a deterministic, goal-oriented systems engineering approach [18]. The unpredictability of complex systems is at odds with this perspective, such that characteristics of complexity such as nonlinear relationships, threshold effects and emergent behaviours are perceived predominantly as threats to system stability and service delivery [3]. Accordingly, most research conducted on infrastructure interdependencies has taken up this stance, viewing interdependency as a threat to be mitigated and protected against.

### **3. INTERDEPENDENCY AS OPPORTUNITY**

Interdependencies have thus far been explored primarily as a negative force, especially in the context of infrastructure resilience, through the lens of the risks they represent through cascade failures and cross-network vulnerability [2, 3, 5, 19–21]. We argue that interdependency is, however, Janusian in nature; representing opportunities as well as risks. In a 2013 workshop bringing together 25 infrastructure stakeholders from the energy, ICT, transportation, waste and water sectors and including representation from industry, academia and governance, Carhart and Rosenberg [17] focused on identifying beneficial interdependencies within and across sectors. Of 77 identified interdependencies, 87% intra-sector and 86% inter-sector linkages were categorised as having beneficial outcomes. This result strongly suggests that the literature focus on interdependency solely as a risk factor is disproportionate and incomplete.

In order to better identify opportunities from interdependency, these opportunities may be organised into a typology depending on the nature and intensity of the interdependency in question. Previous typologies have been proposed by which infrastructure interdependencies can be broadly categorised and understood [1, 17, 22]; our aim here is not to replace or challenge these efforts, but rather to complement them by presenting a typology specifically targeted at the identification of beneficial opportunities arising from these interdependencies.

#### **3.1. Simple opportunities**

On a basic level, the sharing of knowledge across network gaps can inform and improve good practice through exposure to new perspectives and procedures. What might represent standard approaches to ensure secure, efficient or robust design in one system may be novel and applicable to another where such approaches have not previously been explored. Here

the opportunity to increase the efficiency and resilience of systems is primarily a matter of establishing lines of effective communication and collaboration between managers, designers and operators that cross traditional departmental or industry boundaries [23]. While a one-time learning event does not itself represent an interdependency, many interdependency-based opportunities begin with the sharing of ideas (even within a single organisation such as to increase productivity or single-plant resilience) and develop from that basis. This knowledge exchange can then become a simple interdependency by establishing a transactional pathway for the recurring transfer of knowledge and information between system operators. These flows can be intermittent and non-critical to system functioning, thus representing comparatively low risk, but also exhibiting a lesser degree of opportunity than more substantial integrations. We therefore define simple interdependency opportunities as those based primarily on knowledge exchange between practitioners, representing a transactional flow of information that occurs intermittently but repeatedly, that are beneficial but not critical to the operation of the coupled systems.

### **3.2. Geographic/physical opportunities**

The physical co-location of multiple infrastructure systems can present opportunities for cost-saving and increasing system efficiency. This represents essentially an expansion of infrastructure sharing concepts to specifically consider sharing across multiple networks and sectors. The placement of mobile phone network antennae on tall buildings or pre-existing telecommunications masts precludes the need to build independent structures. Technologies to store energy at the point of generation, especially in remote examples such as offshore wind farms and wave-based power generation systems, can use combined structures to reduce building costs and the necessary length of new transmission networks [24]. Similarly, the establishment of power generation and storage technologies at the point of use, such as with residential solar roof panels and home storage batteries currently under development, would also represent a reduction in the loading demands of the transmission network. Such decentralisation will support a considerable increase in system resilience, freeing end users from sole dependence on the national power grid should a failure occur. Geographic/physical interdependency opportunities represent beneficial couplings based on co-location and/or the physical sharing of infrastructure, material or information across systems at a localised scale.

### **3.3. Integrative opportunities**

Within the functioning and management of the networks themselves, interdependencies can enable new opportunities for increasing resilience by applying the advantages offered by one network to the management of another. The concepts of 'smart' infrastructure and the 'internet of things', are fundamental examples of this. Data and information, gathered and distributed by telecommunications infrastructure, are used to actively and efficiently manage decisions and flows in networks of transport, water and power in real time (as opposed to simple opportunities where information flow is used solely to impart knowledge). Integrative interdependency opportunities are thus defined by a synergy and extensive functional interconnection between multiple infrastructure systems at multiple points, representing shared risk as well as significant benefits to the effective functioning of all coupled systems, and improving the delivery of existing services and/or making entirely new services possible [25, 26].

Infrastructures that become overly dependent on this synergy and make use of overly ‘tight’ couplings face the risk of cascade failure, so system design should seek to incorporate redundancy and ‘fall-back positions’ to enable continued functioning if some breakdown occurs. Resilience should remain a key priority and care should be taken to avoid the transition to smart infrastructure being a blind one. Climate and social change will bring uncertain risks, so systems must be engineered to be robust in the face of unknown pressures. With fully integrated complex infrastructure systems, the risks are greater and thus must be recognised and managed effectively, but the potential opportunities are equally more transformative. Our ability to design and maintain resilient infrastructure systems depends on the ability to identify those cases where the opportunities outweigh the risks.

## **4. ECOLOGY AS AN EXEMPLAR OF RESILIENT INTERDEPENDENCY**

### **4.1. Why nature is resilient**

Naturally occurring ecosystems are commonly given as examples of complex, interconnected and resilient systems [27], and as such may offer insight into how such systems can function effectively. Infrastructure systems are analogous to ecological systems in a number of ways: both being highly interconnected, complex and adaptive; both exhibiting characteristic scaling properties; and both relying on flows of material, information and energy [10]. In designing and managing infrastructure systems, there may be lessons we can learn and apply from ecosystems, which largely have evolved to be resilient to disturbance and sustainable within their environment. Myriad feedbacks and interdependencies between numerous species of organisms as well as energy and material flow systems act in nature to increase the resilience of the overall system, rather than merely introducing vulnerabilities. Material and energy flows are resilient in part by being fundamentally grounded in physical laws and chemical processes, but also by functioning in cyclical pathways whereby no material is ultimately wasted. At the system level, resilience is achieved through complexity, with the system possessing self-regulating behaviours and feedbacks that maintain the stability of the system in the face of disturbances [13]. At finer scales, organisms and species are resilient in many cases due to overlap and redundancy among ecological niches; rarely is a ‘role’ in the ecosystem filled by only a single species whose loss would destabilise the broader system through cascading effects.

### **4.2. How infrastructure differs from nature**

By exploring ways in which the relationships and principles found in nature can be applied to infrastructure systems, we find new ways to use complexity and interdependency to our advantage by designing in greater resilience and sustainability to our own global systems. Careful thought and translation will be required, however, as infrastructure and ecological systems share fundamental differences despite their similarities, and are not perfect analogues to one another. Natural systems have, by and large, adapted and evolved to their current stable states through processes of random mutation, high attrition, emergent behaviours and incredibly long time scales in a ‘bottom-up’ manner. Anthropogenic systems

on the other hand, and the concerns that drive them, are traditionally designed from a ‘top-down’ goal-oriented perspective and are intolerant of such long time scales and resource waste. Further, many technological systems have necessarily been developed to operate in a highly controlled and deterministic manner [28] which is fundamentally at odds with the seemingly haphazard way in which natural systems function. Such determinism and reductionist thinking, however, encounters difficulty when considering larger systems, and complexity forces a more integrative and ecological perspective than that which was used to create the system’s components and base functionality [18]. This forced shift in perspective, from a system’s creation based in reductionism and mechanistic design, to a systems approach that recognises and addresses complexity, interdependency and emergent properties, echoes the transition that has been seen in many disciplines over the past half-century, such as Jane Jacobs’ pivotal call for fresh perspectives in urban studies [29] and the steady rise of complexity science in ecology and biology [13]. Individual components and sub-systems are necessarily created with a deterministic perspective; however, at the system scale, human-created infrastructures must work to replicate by design and planning the efficiency and resilience that nature has developed by long-term experimentation.

### 4.3. How infrastructure can learn from nature

Despite the important differences between human and natural complex systems, commonalities exist where the functioning of nature can be applied as lessons for materials engineering [30] and infrastructure design and management [31], enabling interdependencies to be viewed as opportunities. In his book ‘The Web of Life,’ Capra [13] presents five principles of ecology and system survival and discusses ways in which these lessons can be applied to human society in the pursuit of sustainability. Here, we consider how these principles can specifically be applied to infrastructure design and management (Table 1).

**TABLE 1.** Principles of ecology and system survival [13], and examples of how they can be applied to infrastructure to build resilience and sustainability

Principle	Ecological Description	Infrastructure Relevance
<b>Interdependence</b>	Members of a community are connected in a vast and intricate network of relationships via multiple feedbacks that create non-linear response patterns.	<ul style="list-style-type: none"> <li>• Reliance on outputs as inputs between infrastructures</li> <li>• Information feedback to optimise functioning (e.g. smart metering)</li> </ul>
<b>Cyclical Flow</b>	Nutrients are recycled so that waste of one species becomes food for another. Organisms are open systems but ecosystems are largely closed with respect to materials.	<ul style="list-style-type: none"> <li>• Avoidable waste reduction/ circular economy/ engineering for re-use</li> <li>• ‘Closing the system’ by accounting for externalities, e.g. carbon tax systems</li> </ul>
<b>Partnership and Cooperation</b>	Co-evolution, symbiogenesis and mutually interdependent adaptations	<ul style="list-style-type: none"> <li>• Infrastructure sharing (asset focus – cost efficiency)</li> <li>• Sharing economy (society focus – enhances well-being and community)</li> </ul>
<b>Flexibility</b>	Continual adjustment to feedback in response to constantly changing conditions. Negative feedbacks facilitate stabilisation after disturbance or a shift in conditions.	<ul style="list-style-type: none"> <li>• Adaptability to uncertainty (e.g. climate change)</li> <li>• Responsive traffic routing</li> </ul>

		<ul style="list-style-type: none"> <li>• Optimising for multiple objectives rather than maximisation to one</li> </ul>
<b>Diversity</b>	Pluralistic resilience, biodiversity with overlapping ecological functions that can partially replace one another	<ul style="list-style-type: none"> <li>• Distributed/pluralistic energy storage and generation</li> <li>• Multiple network pathways</li> </ul>

The importance of Capra's first principle, *interdependence*, is already well-known in infrastructure contexts, but with focus usually placed on negative aspects such as vulnerability and cascade failure risks as previously discussed. As in nature, and as explored above in the proposed threefold typology, there are also many ways in which these interdependencies can be exploited in a positive sense. Smart metering of residential electricity consumption, for example, is growing in interest and uptake in various locations. This ability to provide consumers with detailed and timely feedback has the potential to inform purchasing and lifestyle decision-making toward more energy efficient behaviour, provided the feedback is adequately clear and informative [32].

The second principle, *cyclical flow*, is something that human systems have taken steps to transition toward but more progress is required to ensure sustainability and efficiency. The re-use and recycling of materials, reduction in avoidable waste, and engineering of products for long-term use rather than disposability are all actions that will serve to increase sustainability at a society-wide scale. As organisations transition away from a solely competitive perspective and consider circular economies and industrial symbiosis, benefits become apparent for both the industrial community and long-term global sustainability [33]. This principle, in an infrastructure context, primarily concerns flows of materials and resources but is closely linked to, and dependent upon, partnership and cooperation between organisations and industries.

*Partnership and cooperation* are developing in many industries and sectors as interest grows in systemic thinking, conducting interdisciplinary research, and bridging gaps between sectors and networks that have previously operated independently. The drive to develop in this way is largely a reaction to the growing complexity of global human-made systems, which cannot be effectively managed and responded to by organisations remaining isolated and purely competitive. At all three levels of interdependent opportunity identified above, partnership and cooperation are required and, increasingly, becoming present. Knowledge exchange between organisations has become commonplace in industries preparing to face climate change, particularly where encouraged by government reporting programmes [4]. Infrastructure sharing approaches (variously referred to in terms such as common carriage, unbundling, track sharing, etc. depending upon industry context) represent geographic/physical opportunities already widely exploited by numerous industries to mutual economic benefit [34]. Efforts to develop smart networks and infrastructure for efficient energy use and material routing represent a strong integrative opportunity dependent on cooperative arrangements.

*Flexibility* is a principle whose importance has been highlighted by the need for infrastructures and industries to adapt to the uncertain conditions caused by global climate change. Efforts to build resilience to future disturbances, the exact nature and intensity of which remain unknown, necessarily require a great deal of flexibility and capability to adapt to changing circumstances. Rigid systems that are optimised to function only under a narrow set of external conditions will face a high risk of failure when subjected to extreme circumstances outside of the designed conditions. Systems that are able to adapt to these circumstances while

maintaining or improving their intended functions will prove much more resilient to future disturbances. The possible ways in which driverless vehicles might be coupled to efficient routing and vehicle sharing could transform the use of transportation infrastructure in major cities, shifting personal transport from an owned asset to a shared service. This would represent a flexible solution with benefits to urban congestion, emissions-based pollution and manufacturing demand [35].

Finally, the principle of *diversity* is exemplified clearly in nature by the multitude of species, functional groups and ecosystems that we observe; however its implementation in human systems can be one of the greatest challenges. In large infrastructure networks, it is recognised that redundant linkages play an important role in maintaining functionality should a part of the network fail or saturate, offering diversity in the sense of multiple flow pathways. However, beyond the mitigation of perceived immediate risk, excess redundancy may be viewed as wasteful by decision-makers and stakeholders if the benefit to resilience is not internalised. Conventional practices have also tended to favour mass production, providing a financial incentive to populate networks and systems with an overabundance of a single design or approach. In many cases this can be efficient, but this low diversity may represent a vulnerability should a failure prove specific to that design or approach. The recent uptake of 'lean manufacturing' and agile production processes seeking to reduce waste while maximising efficiency and adaptability [36] represent a change to this paradigm. In the energy industry diversity is present in sources of electrical generation, which provides some resilience to disturbances in the availability of fuel resources. Current research into battery technology and the possibility of distributed, mobile and/or residential electricity storage also represent a diverse approach, smoothing temporal discrepancies between supply and demand [37]. Such 'micro-storage' approaches would provide backup sources of energy to increase resilience across the entire network, especially when coupled with distributed generation (e.g. residential photovoltaic roof panels) and managed using smart grid technology to optimise timing, costs, and social benefits [38, 39].

Understanding and analysing integrated infrastructure networks as holistic 'systems of systems', as one would an ecosystem, is the first essential step in moving beyond an isolated and sectoral approach and enabling a complete understanding of system dynamics [10, 40]. When understood in this way, system-level optimisation and management for broad-reaching global interests become realistic possibilities. Further, the recognition of commonalities between infrastructure networks and ecological networks (itself exemplifying a simple, knowledge-based opportunity) allows us to adapt our own engineered systems and appreciate the ways in which they can benefit from complexity. When incorporated into organisational business models, and thus directly embedded in the guiding principles of how industries operate and create value [41], sustainability and resilience may become much easier and more natural issues to tackle.

#### **4.4. Barriers to and enablers of opportunity**

Opportunities can be recognised or driven in numerous ways, but several specific areas may be considered from our Janusian perspective as either key barriers to or enablers of interdependency-based opportunity. First, existing *technology* can act as a limiting factor in the realisation of new innovations, but as it develops new opportunities may emerge that were



previously unfeasible. This is evidenced in the growth of smart systems, renewable energy generation and increased efficiency in a variety of systems. Second, *design and innovation* play a key role in re-evaluating how systems can function more effectively, such as through the adoption of circular economic principles and the consideration of green and blue infrastructure. If design perspectives are open to new ideas and creative thinking, rather than resistant and entrenched in conventional practices, opportunity is possible from innovation. Third, how we consider the *maintenance* of built systems influences the efficiency and effectiveness with which they are managed, largely in terms of whether maintenance activity is only reactive to faults or preventative and thus forward-looking. Fourth, *governance* can act as a barrier to opportunity if regulatory structures are rigid, but equally capable of enabling opportunity through careful and informed consideration of how public policy, regulation and legislation can and should adapt to changing conditions. Finally, societal *behaviour* is fundamental in determining whether innovations will be met with resistance or acceptance. Demand-side responses to service delivery and an awareness of the context and implications of consumer decisions are thus critical for enabling new opportunities.

## 5. CONCLUSIONS

Due to the way they have been historically developed, infrastructure systems traditionally tend to be silo-bound; built and maintained in ways that discourage systems thinking and treatment of interdependencies. Future efforts need to capture the 'system of systems' view and work across conventional boundaries in order to plan and manage infrastructure systems in the wider context of one another and with regard to long-term benefits and risks to human well-being.

Research and policy have largely focused on the negative aspects of interdependencies and the risks they represent to resilience; however, further attention is warranted on the opportunities they may represent. The risks represented by global climate change (and the interdependencies they highlight) have driven a recognition of the need for organisations to consider these risks and adapt to them together [4, 42]. By a similar token, infrastructure design and management must recognise the risks and opportunities presented by interdependency and adapt accordingly to these as well. However, we advocate here that the focus on interdependency be pulled away from solely considering risks and vulnerabilities, and seek to recognise and embrace the myriad opportunities that exist. Numerous projects exist, either in theory or in practice, which are beginning to recognise and exploit these opportunities [23, 43–47]. Such projects can range from adaptations of existing infrastructure systems to novel disruptive business models that seek to replace entire supply chains and conventional approaches [48, 49].

The typologies proposed in this paper represent a way in which the opportunities associated with interdependency can be more effectively recognised and exploited. To further recognise and understand opportunities in future efforts, several dimensions should be considered: 1. what is the intensity of the opportunity? Is it a true two-way interdependency, and if so how strong are the linkages? If not, is it a one-way dependency or simple co-location, and might it develop into a true interdependency, either deliberately or unintentionally? 2. Has the opportunity been planned in advance, or has it been recognised and exploited based on pre-existing systems? Or is it completely emergent and serendipitous? 3. What specific value does

the opportunity offer, i.e. what is its business case? Does it provide increased resilience, an engineering benefit or a cost benefit? Are the benefits represented in the market (i.e. monetary) or not (e.g. societal well-being)? 4. What are the spatial and temporal scales of the benefits? How large a geographic area do they impact, and when in the project's life cycle do they factor in? 5. Finally, how do the benefits weigh against the risks? All of the above dimensions can and should be used to explore both opportunity and risk, and consider them in the context of one another in order to weigh the overall value of interdependent efforts. Accurately recognising and understanding opportunities from interdependency will aid practitioners and decision makers in making informed choices as new innovations are pursued. Transitioning our thinking toward the proactive recognition and pursuit of opportunities from complexity, rather than only in reaction to threats, will have powerful and far-reaching benefits for global well-being.

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## 5. ASSESSING THE ‘GOVERNANCE GRIP’ OF COMBINED AUTHORITIES FOR INTEGRATED INFRASTRUCTURE PROVISION IN THE UK

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**ABSTRACT.** While the positive benefits of integrated infrastructure development and management are theoretically understood, many global city-regions do not have governance arrangements designed to operationalise integration. Despite the criticality of ‘nexus’ provision and high degrees of interdependence in city-regions, the organisation of governance mechanisms to ensure collaborative and symbiotic relationships remains an incomplete aspect of business as usual. A preliminary assessment was conducted of the governability of critical infrastructure domains (water, energy, food, and waste) in select UK city-regions. To establish a systematic approach for further research, a Governance Framework was produced and piloted. The paper also reports on preliminary investigations and confirms insights that a governance deficit exists. We note that integrated infrastructure issues were not appearing systematically as high-level strategic governance priorities for the newly established Combined Authorities. We conclude the ‘governance grip’ discernable for overseeing integrated infrastructure outcomes is relatively weak.

**Keywords:** Integrated infrastructure, Governance and Power, Nexus, Combined Authorities, United Kingdom.

### 1. INTRODUCTION

Sustenance and prosperity in cities and regions are built upon well-functioning infrastructure. The UCL City Leadership Laboratory (CLL) developed a method and conducted a pilot assessing the ‘governability grip’ of Combined Authorities and City Councils and their governance fundamentals for integrated urban infrastructure oversight in relation to water, food, energy and waste. The paper reports on this research conducted to assess the governability of critical infrastructure domains (water, energy, food, and waste) in select UK city-regions.

Fundamental in determining the resilience (or fragilities) of cities and regions, 'nexus' infrastructures underpin the systems of provision for 'liveability'. Strategic planning and investment decisions in infrastructure systems provide medium-term 'steering' to advance system performance and connectivity. This paper sets out initial findings about future directions for system coordination and pathways for governance improvements, given the range of roles and responsibilities. The task ahead, that is in part illuminated, is revealed as a significant challenge even in the context of advanced economies.

## **2. BACKGROUND**

The mix of public and private systems in the nexus spheres of water, energy, food, and waste vitally underpin daily city-region functionality and ability to sustain shocks. While conceptually the positive benefits of integrated infrastructure, in development and operation for mutually supportive and coordinated infrastructure systems, are understood, day-to-day delivery practice arrangements are not necessarily designed to reflect this. Despite the criticality of nexus provision and high degrees of interdependency in city-regions, the organisation of governance mechanisms to ensure collaborative and symbiotic relationships remains an incomplete aspect of business as usual.

### **2.1 Governance agents**

Local or regional governments are positioned as a key coordination node on behalf of all citizens as the tiers below the national interest represented by that nation state. There are a mix of local actors at differing levels of focus and resolution for infrastructures in the UK. At the Combined Authority regional level, with a strategic function tasked with looking ahead, the way a local government role is conducted can typically play out at three main levels:

- (i) *Making it work better now* – attaining optimal and integrated business as usual system performance in the short and medium-term;
- (ii) *Improving prospects ahead* – improving strategic infrastructure development and long-term investment for a more functional and resilient future; and
- (iii) *Leading response and recovery* – contributing to, or spearheading crisis response and recovery, with emergency management services and providers when short-term system failure occurs.

In combination, these roles concurrently shape the assuredness in a city-region as somewhere to live with a secure quality of life and invest in the future with confidence. While doing better crisis management can potentially help inform priorities to mitigate short-run problems, our interest is in the strategic medium to long-term city-regional level role of public governance.

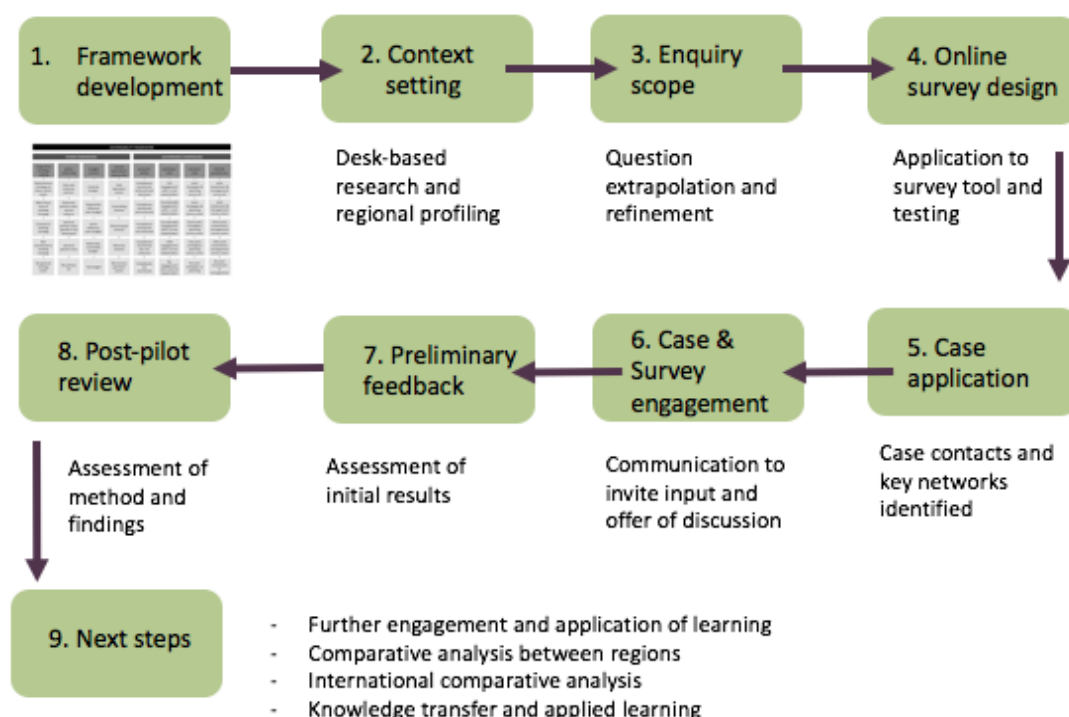
### **2.2 Motivation for research**

Devolution of responsibilities in the UK provides a series of challenges and opportunities for leadership of complex issues where integrated solutions can generate clearly positive

outcomes. In particular, political deals run from the national government level mesh growth and devolution arrangements for ‘devo-deals’ in England that attempt to package spatial rebalancing and regional ‘powerhouse’ investments with new institutional arrangements, such as city-regional mayoralties [1]. New mayoral leadership in the new Combined Authorities presents the opportunity for the emergence of coherent strategies, new alliances and connectivity, and the spectre of regional strategies and downstream integrated decision-making. Within this context of change, research that can support the case, and provide insights, for the focus of new strategic endeavour at the Combined Authority level is useful. Assisting to empower the institutional construct and intermediary functions possible, with the role of mayoral leadership being exercised as more than that of a figurehead, can improve nexus outcomes.

## 2.3 Method overview

This paper focusses on reporting the first phase of a wider research programme. It broadly comprised of three general steps: (1) assessment method development resulting in the ‘Governability Grip’ assessment framework; (2) preliminary testing; and (3) theorization of internationalisation and wider application. Our work following the following methodological steps summarised in Fig. 1, which were undertaken over three months in early 2017.



**FIGURE 1.** Methodological Overview

## 2.4 Operating context

In the context of English devolution-oriented ‘city-deals’ and the potential for localised empowerment of economic, urban and infrastructure development—regional resilience building is a fundamental component of strategic foresight and delivery. Attending to the stability of existing key infrastructure foundations, bolstering the dynamic strength of these systems, and realising new potential to unlock growth requires intentional steps given institutional histories and current coverage of the ‘nexus’ of provisions that underpin successful long-run regional development.

With a focus on select Combined Authorities with mayoral elections in 2017, analysis was conducted to produce an early formative view on the state of the respective areas fundamental nexus resilience or fragility, with an assessment of their ‘grip’ on the issues, particularly at the level of improving strategic infrastructure development and investment. At the heart of the research was a quest to understand the nature of accountability as it stands, and to test what it might need to be for improved oversight and management in the near-term future. On this basis, new insights for advancing ‘governability’ and coordination were envisaged as part of an ongoing research programme.

Extending the scope and integrative power of Combined Authorities to use their new role – and leverage potential leadership – of local governance functions, working from areas such as local transport and business incentives as part of driving industrial strategy, can open up new investment strategies and a multitude of opportunities. A transfer of power to revitalise regions, with enhanced regional governance capabilities to lead develop with a primary economic and labour market orientation, presents the opportunity to dovetail integrated regional resilience strategies alongside strategic leadership and planning system improvements to present a step-change.

### 3. RESEARCH FRAMEWORK

Before outlining the framework, we briefly introduce the key concepts of governance, power, the nexus, and resilience that underpin the analytic framework developed.

#### 3.1 Key concepts

**Governance** – in this research our starting point is that governance at a basic level is simply the system of governing through which provisions are delivered [2]. Recognising that the term is used to denote the informal dynamics of ‘steering’ encapsulate in activity within public and private policy networks, we note usage is wider than ‘government’ which references more explicitly the formal channels of the state [3]. However, in this work our specific applied conception is focused on the formal governmental ‘governance’ aspects of oversight and control of defined physical infrastructure systems in the nexus. In other words, our focus is constrained to the institutional mechanisms of apparent in government.

**Power** – Power in context of this research is constrained to consideration of the degree of control or influence local authorities as governments exert over critical infrastructure [2].



Power is “inextricably linked” with fundamental elements of governance [4], which has also been highlighted within the context of resource nexus governance [5]. Different types of power may be exercised and applied via formal and informal channels and measures. Our focus was to seek to gauge the degree of influence visible through the analysis of formal documentation. Therefore, we do not engage in a nuanced and differentiated analysis of power as a political or institutional concept.

**Nexus** – we take a nexus perspective, as the viewpoint brings attention onto how robust systems are in a particular location, and to what extent they are adequately understood and made transparent for improving integrated management, maintenance and investment decision-making. For this research the critical infrastructure provisions called the nexus are the sectors of energy, food, water, and the resulting household waste outflows<sup>11</sup>. These four core flows were selected because these provisions are fundamental to life in an urban world; food and water are vital to human sustenance, with energy used to produce, distribute and consume these resources, and waste generated as part of these processes. Within this research, these are defined as follows:

- **Energy:** gas and electricity supply;
- **Food:** supply of food;
- **Water:** supply of potable water; and
- **Waste:** as produced by these three sectors. The particular types of waste in focus are:
  - **Energy waste:** greenhouse gas emissions;
  - **Food waste:** includes both organic and packaging waste, therefore covered by non-hazardous waste; and
  - **Wastewater:** covers sewage water.

Understanding the nature and governance of nexus systems and testing the direction required for improved oversight, helps to reveal interdependencies that can highlight governance challenges, risks and opportunities.

**Resilience** – with its conceptual roots in seeking to illuminate the connections between social-ecological systems (e.g. Holling, 1973) [6], resilience has become a mainstream concept in the urban infrastructure field primarily as a signifier of system flexibility and capacity to absorb and recover from system stresses and failure. Understanding resilience as the capacity of a system to experience shocks while retaining functionality, recognizable identity and feedback mechanisms, as in Walker et al. (2006) [7], enables consideration of shifts among different system configurations [8]. An integrated infrastructure set of arrangements is a mainstream requirement for stable, sustainable and enduring urban platform.

### 3.2 Constructing a framework

To establish a systematic approach for further research on the ‘governance grip’ evident on key infrastructures, a Governability Framework was produced and piloted. Eight domains were generated in two categories representing the power and governance dimensions. Previous research undertaken by the UCL CLL in collaboration with C40 and Arup, resulting in [2],

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<sup>11</sup> This is aligned with the UK’s Engineering and Physical Research Council (EPSRC) understanding of the nexus. Source: <https://www.epsrc.ac.uk/files/funding/calls/2014/sandpitwaterenergyfoodnexus/>

categorised power into four dimensions, which were tailored to apply within this research context: long-term strategy setting, policy enforcing, budget control, and service operation and ownership. Long-term strategy setting focuses on the level of control local authorities have over long-term strategic plans. A strategic plan is defined as a document that sets out strategies to achieve vision(s) and objectives. Policy enforcing covers the level of control local authorities have over policy setting. Policies are defined as the particular rules set to deliver action. Budget control covers the level of control local authorities have over budgets.

The final component, service operation/ownership, focuses on operation and ownership of the services rather than ownership of the asset itself. Ownership of energy, food, water and waste are not considered in this research as these discussions themselves have been the focus of research projects. The concept of ownership depends on the legal system and what rights are perceived to constitute it, e.g. [9-10]. The ownership of services is often very clear as this is contractually stipulated, while the discussions in relation to the assets themselves are sometimes more complex. For example, waste flushed into a watercourse or leaving premises in the form of atmospheric emission is the “ultimate externality” and owned by no one [11], and the interconnectedness of water on our planet results in discussions of water as a common treasury [12-13]. There are thus both very clear areas and grey areas in relation to assets, resulting in our focus on ownership of services.

A literature review identified four relevant governance dimensions: accountability, participation, connectivity, and interdependencies. Accountability for the purposes of this research is understood as the transparent relationship between the Combined Authorities and their external actors (e.g. citizens, universities, non-governmental organisations (NGOs)), where Combined Authorities are responsible to the external actors for their actions, e.g. [14-19]. Participation of actors external to the Combined Authorities (e.g. citizens, universities, NGOs) was examined in strategic decision-making on the operation of services, as well as the level of engagement by external actors [20-23]. Connectivity is understood as the functional connections between the nexus sectors through joint strategies and joint planning [24-25]. The final component of interdependences between nexus sectors is understood as governance and management connectivity. This is explored by examining joint investment and joint management (i.e. where there are shared mechanisms of management) [24].

For each of these dimensions, the level of influence and control was coded from 0 to 4. This framework, and the meanings of the code for each component, is outlined in Fig. 2.

GOVERNABILITY FRAMEWORK								
POWER DIMENSIONS				GOVERNANCE DIMENSIONS				
	long-term strategy setting	policy enforcing	budget control	service operation/ ownership	account-ability	participa-tion	connect-ivity	interde-pendencies
4	Autonomous strategy on nexus sector exists	Sets and enforces policies	Controls budget	Sole operator/ owner	Compliance monitored, enforced and disclosed	Full engagement with >2 ext stakeholders	Joint strategies & planning across all	Joint investment & management across all
3	Main focus area of existing strategy	Particular policies exist; cannot enforce	Substantial influence over budget	Controlling interest	Compliance monitored and enforced	Considerable engagement with > 2 ext stakeholders	Joint strategies & planning across some	Joint investment & management across some
2	Covered in existing strategy	General policies exist; specific to be developed	Some influence over budget	Shared equal interest	Compliance monitored, not enforced	Considerable engagement with 1/2 ext stakeholders	Some joint strategies/ planning across some	Some joint investment/ management across some
1	Not mentioned in existing strategy	General policies exist	Nationally controlled budget	Minority interest	Compliance monitored but not enforced	Little engagement with 1/2 ext stakeholders	Few joint strategies/ planning across some	Little joint investment/ management across some
0	No general strategy exists	No policies set	No budget	Not service operator/ owner	Compliance not monitored	No engagement with external stakeholders	No joint strategies or planning	No joint investment or management

**FIGURE 2.** Governability Framework

## 4. TESTING THE FRAMEWORK

Within the constraints of the project, preliminary testing occurred to verify the potential value of the framework. The application and engagement undertaken are outlined, along with illustrated examples of proposed findings.

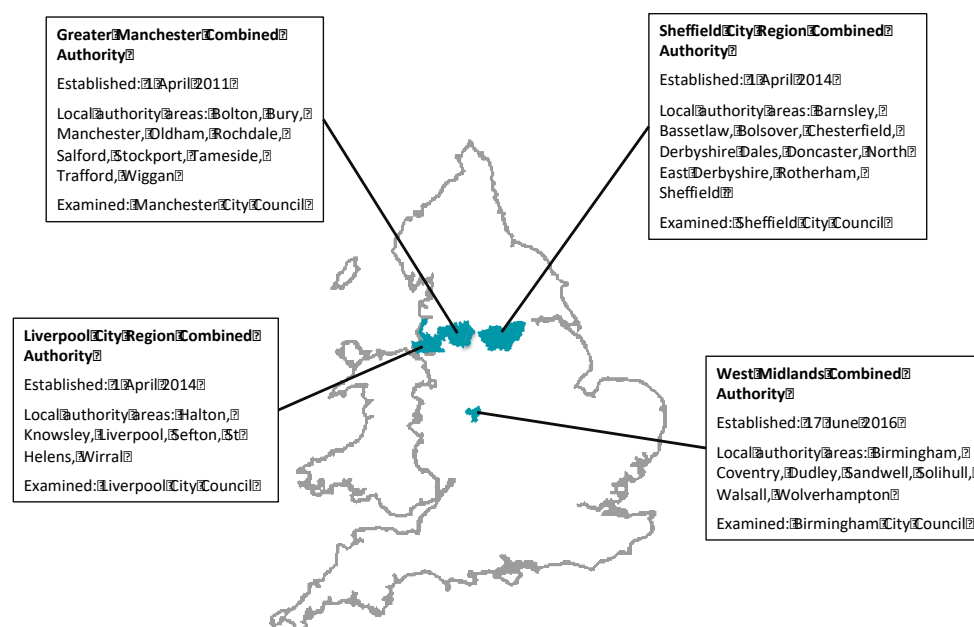
### 4.1 Framework application

With a view to establish a base-case from which to monitor, the initial focus was on preliminary engagement with select case studies for the purpose of identifying early insights and scoping future research into directions for system coordination improvements. The applied methodology proposed tested composed of an online survey and a supplementary interview with key people in local government in each case.

### 4.2 Preliminary engagement

The piloting phase saw select preliminary sampling undertaken in four UK city-regions pre-formation of new Combined Authorities. It examined four Combined Authorities, namely: Greater Manchester Combined Authority, Liverpool City Region Combined Authority, Sheffield

City Region Combined Authority and West Midlands Combined Authority; and a city council within each of these being Manchester City Council, Liverpool City Council, Sheffield City Council and Birmingham City Council. Figure 3 provides further case study information:



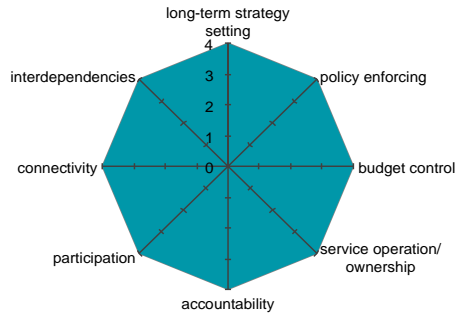
**FIGURE 3.** Case Studies

### 3.3 Presenting results

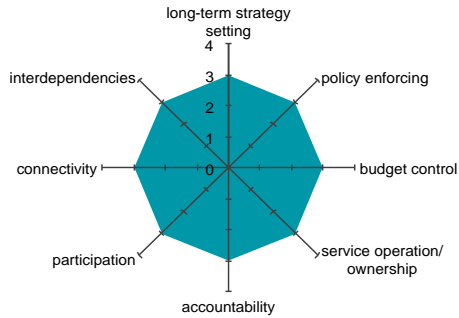
We employ spider diagrams as they offer a useful visual representation of the findings to both comprehend results and compare cases. Figure 4 (Spider diagrams – hypothetical findings) shows four hypothetical results ranging from a strong (substantial) to weak (limited) grip on governability, with a uniform result in each component used<sup>12</sup>.

<sup>12</sup> Note there is no coding for the participation, connectivity and interdependencies components in the spider diagrams. This is because solely desk-based research would give strong and skewed responses for this (as these are the less transparent during online research) and no survey responses on these components were received.

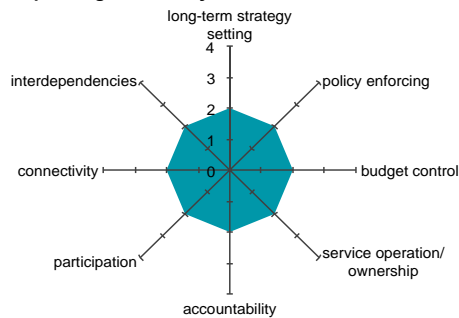
**Uniform substantial governability**



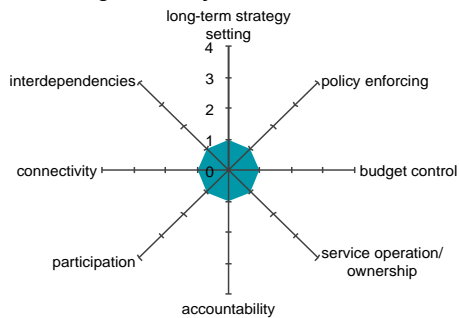
**Uniform significant governability**



**Uniform partial governability**



**Uniform limited governability**



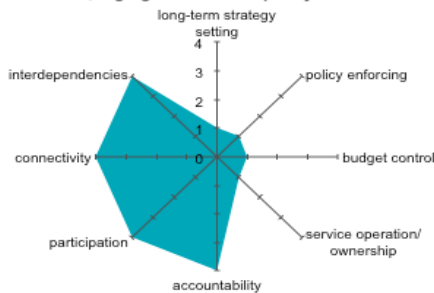
**FIGURE 4. Spider diagrams - hypothetical findings**

An example of the case study results is presented in figure 5 (Illustrative findings). They show that across all nexus sectors there is a low-mixed governance grip discernable from the testing conducted. The cases generally exhibit low to medium influence over the power components, and do not infer a formal and transparent systematic approach through our lens of analysis.

**Substantial control, low governance capacity**



**Some influence, high governance capacity**



**Mixed governability**



**Mixed governability**



**FIGURE 5. Illustrative Findings**

## 5. FINDINGS

This section outlines and discusses the key findings and implications derived from the pilot to date. At a high level, we consider:

- It is too early to see evidence of intention or clarity of action at a regional level of integrated regional infrastructure strategic development, and furthermore;
- Combined Authorities are not clearly positioned for a strategic role leading long-term investment and integrated regional resilience.

Consequently, there are readily discernable gaps in governance, both a policy process and institutional design level. We now elaborate further and propose policy-style advice off the back of the research [26]<sup>13</sup>.

### 5.1 Preliminary findings

An emphasis on assessing the governability grip through the current and emerging institutional architecture brings into focus for us the 'direction of travel' for infrastructure system performance improvements that can lead to integrated and resilient outcomes. Despite the criticality of 'nexus' provision and high degrees of interdependency in city-regions, the organisation of governance mechanisms to ensure collaborative and symbiotic relationships clearly remains an incomplete aspect of business as usual in the context of emergent region-level governance authorities.

As noted, our preliminary investigations confirm the primary insight that a governance deficit exists. In short, integrated infrastructure issues were not appearing systematically as high-level strategic governance priorities or in mayoral discourse for the newly established Combined Authorities. While this reflects an emphasis on local 'burning platform' political issues, it points to the emphases mayoral candidates had to more immediate and local issues such as inclusive economic growth, regional promotion and employment<sup>14</sup>. This in many respects mirrors the set of common concerns embodied in the national-level political sphere and the extension of more local concerns, to representation the formation of a new intersection between them.

In summary, the advisory direction that emerged from our work was:

- Regional resilience building of critical infrastructures is a fundamental component of economic, urban and infrastructure development now for the future.
- It is too early to see evidence at a regional level to support the idea of developing integrated economic, social and environmental strategies to progress long-term integrated decision-making.
- As currently configured, Combined Authorities are not clearly positioned as the new nodes of governance for strategic long-run investment and integrated regional resilience.

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<sup>13</sup> This draws from our report at the UCL City Leadership Laboratory (CLL) website: <https://www.cityleadership.net/nexus-urban-infrastructure> [25].

<sup>14</sup> For example, Mayor Andy Street and Mayor Andy Burnham's priorities for West Midlands Combined Authority (WMCA) and the Greater Manchester Combined Authority (GMCA) respectively. Sources: <https://blog.bham.ac.uk/cityredi/andy-streets-to-do-list-challenges-for-the-new-wmca-mayor/>; and: [https://www.greatermanchester-ca.gov.uk/homepage/57/the\\_mayor](https://www.greatermanchester-ca.gov.uk/homepage/57/the_mayor)

- Better strategy and delivery could extend the scope and integrative power of Combined Authorities to utilise their role to leverage leadership for significant integrated infrastructure provision and performance improvements.
- As it stands, it is plausible to claim there is a 'governance deficit' or an 'ungoverned' aspect of integrated infrastructure investment for high performance long-term growth.
- There are gaps between the spatial concerns of local Councils and the emerging regional interests of Combined Authorities, and the national interest orientation of central government.

## **5.2 Preliminary implications for Combined Authorities**

Consequently, we asked the question: what does this mean with Combined Authorities mayoral elections in some UK regions? In short, our advice was issued as follows:

- There is scope to take the opportunity to dovetail integrated regional resilience strategies alongside new leadership and planning for economic and whole-of-system improvements.
- The current degree of devolution and power-sharing arrangements between local councils and Combined Authorities will need to develop and mature to get genuine coordinated and coherent investment planning for improved economic performance and community resilience.
- There is potential to develop a firmer and stronger governability grip on integrated infrastructure planning, investment and delivery.

## **5.3 Methodological reflections**

Given time and resources, combined with timing of the mayoral elections, we experienced low uptake on direct engagement and access via the survey and preliminary interviews. Additionally, those who did undertake the survey online and un-coached, did report experiencing some difficulties committing to the categories established in the questions. This suggests the value of face-to-face or telephone coached survey responses as being a superior method to get better quality and more accurate engagement results.

In general, we note that with the power dimensions there was clearer shared understanding evident, whereas the governance dimensions introduced more interpretative elements and increased subjectivity given the nature of the categories. Furthermore, as with all research engagement that seeks to understanding a complex contextual situation that is changing, we acknowledge the value of longer-run ongoing relationships for research continuity.

## **5.4 Future work**

Future work in 2017-18 is planned to focus on tangible ways to advance local government practice, to add local value in the regions where practice is investigated, including the Greater London city-region later in 2017. It is anticipated this research will be of interest to some Whitehall departments, the National Infrastructure Commission (NIC) and other interested

parties and providers in the infrastructure sphere. As the framework also holds the potential for international application, it is anticipated this will also be explored in due course.

## 6. CONCLUSION

This paper is anchored-off the core premise that the prosperity of cities and regions built upon well-functioning infrastructure will have superior future prospects than those who do not. In its broader quest to advance the governance of integrated infrastructures relating to the life-support 'nexus', the team developed an approach to systemically generate new understanding to build knowledge to support getting better governance attributes for integrated outcomes. Subsequently, a pilot was conducted to assess the 'governability grip' of Combined Authorities and City Councils, and their governance fundamentals for integrated urban infrastructure oversight in relation to water, food, energy and waste. The paper reports on the first step of this work, which included some select sampling in UK city-regions in the early stages of formation, with impending mayoral roles, in relatively new Combined Authorities.

We signalled preliminary findings about future directions for system coordination and pathways for governance improvements, given the range of roles and responsibilities undertaken at a local and Combined Authority level. The challenge, that is in part illuminated, is considered rateable as significant in the context of the UK's scale and socio-economic conditions. Strategic planning is under-developed and investment decisions not fully transparent in infrastructure systems that provide the system directionality and medium-term settings for integrated performance and connectivity. We found there to be wide ranging and unrealised potential to develop a firmer governability grip, exhibiting both more strategic coherence and more applied action at an operational level for integrated infrastructure planning, investment and delivery.

## ACKNOWLEDGEMENTS

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We thank those who participated in our preliminary testing of the framework who were working in local government. We also acknowledge Dr. Jenny MacArthur's continuation of this workstream for the CLL, that goes beyond the first step of development conducted that this paper reports.

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## 6. ARTICULATING CIRCULAR ECONOMY DIMENSIONS IN SPACE: SIX CASE STUDIES

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**ABSTRACT.** Transition from linear to circular economy (CE) is a complex multi-actor, multi-level, multi-phase and multi-pattern process [1]. It requires new pathways weaving together technological, governmental, societal, behavioural, economic and environmental dimensions [2] into sustainable and equitable [3] circular futures. Since CE ultimately manifests in space this paper proposes place-based reflections on CE transition. The paper focuses on two Flemish regions, Antwerp and Central Limburg, investigating how circularized resource flows could simultaneously densify settlement patterns and initiate infrastructural synergies. Firstly, the paper articulates how circularity imaginaries produced in six research through design (RTD) investigations synthesize some of CE's complex system changes in space. Furthermore, this paper investigates the roles these future imaginaries played in processes supporting the two regions' circular territorial developments. Demonstrating RTD's capacity to synthesize multiple CE transition dimensions in place-based future imaginaries, this paper aims to contribute to transdisciplinary research methods supporting multi-dimensional CE transition.

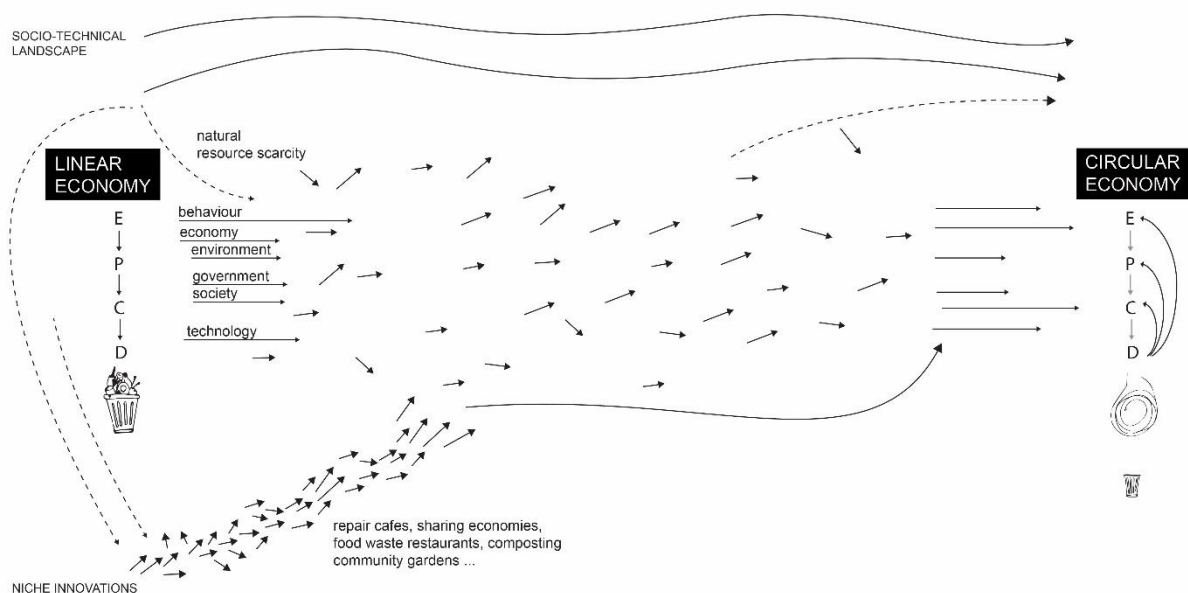
**Keywords:** Urban Metabolism, Research Through Design, Flemish Policy, CE Transition

### 1. INTRODUCTION

#### 1.1 Circular economy (CE) as a multi-dimensional question

In a linear economy industry extracts natural resources to produce single-use products, discarded after consumption. [4] As The Club of Rome already pointed out in the 1970s, the planet's limited natural resources cannot keep supporting wasteful linear economies and lifestyles. [5] In the coming decades materials like oil, gold, silver and metals as well as ecosystems such as coral reefs and agricultural lands will deplete. [6] Europe, housing limited natural resources itself, will become increasingly vulnerable to resource scarcity. [7] Circular economy (CE) is supposed to offer a way out of increasing material prices [4] and more importantly the potential collapse of natural ecosystems. CE aims to achieve economic and resource stability, considering waste as resource. Limiting industry's dependency on nature's resources through reuse, repair and recycling, CE rebalances human dependency on natural resources. [4] CE increasingly appears in regional and local policy documents [8-10] as a means to optimize materials lifecycles. However, it has been criticized for lacking biophysical, institutional and social dimensions. [3] According to Pomponi and Moncaster current CE research seems characterised by partial approaches, not truly accounting for the complexity

of all the dimensions involved. They state that interdisciplinary research weaving together technical focuses and wider social, economic and environmental perspectives is essential to promote and implement multi-dimensional circularity. They propose six dimensions for building research in CE: technological, governmental, societal, behavioural, economic and environmental. [2] Figure 1 schematically shows recalibration of these multiple dimensions in a complex and messy circular economy transition trajectory. It interprets Geels et al.'s transition scheme requiring multilevel landscape, regime and niche interactions. [11] In CE transition, the main landscape change is natural resource scarcity. Niche innovations are amongst others sharing economies, repair cafés and community composting initiatives.



**FIGURE 1.** Diagram multi-dimensional transition from linear to circular economy. C=consumption, D=disposal Source: diagram by author based on Geels 2007 p. 401 [11] Pomponi and Moncaster [2] and EMF [4]

## 1.2 CE Transition in Flanders

The Flemish Government's vision for 2050 declares the shift from linear to CE as one of seven transition priorities. Adopting CE as a cross sectoral ambition, *Visie 2050* calls for a fundamental culture shift to collaboration, innovation, experimentation and self-reflection on Flemish Government regulations and policies. [12]

As early as 2012, the Flemish Waste Agency (OVAM) turned around its policy from 'waste management' to 'sustainable materials management'. [9] Focus shifted to waste as a resource, catalysing transition to circular Flemish economy. These policy shifts amongst others incentivised large and small scale 'circular' clean technologies such as remining waste from former landfills [13] and advancing recycling and reuse applications.

However, civil society calls to attention that realizing integrated socio-ecological CE requires more than 'technofixes' or purely technical solutions obsessed with resource efficiency. [14] Local repair cafés and zero-packaging supermarkets are examples of complementary economies embedded in social networks while reducing waste.

### 1.3 Research Through Design (RTD) on CE

Recent transition literature inquires how place-specificity and multi-scalar characteristics matter for transition. [15] Therefore, this paper proposes place-based and site-specific reflections on CE transition. In the end, raw materials and waste flows find their beginning and endpoints in the landscape, in quarries, natural areas, landfills and incinerators supporting production and consumption cycles. Hence, urban and natural areas, by nature transforming resource hinterlands, should be prominent research arenas in CE transition.

Flemish Policy progressively adopts RTD as an instrument supporting increasingly complex societal planning processes. RTD helps to imagine possible futures [16], combining research rigour with design imagination. As such, RTD produces spatial proposals stimulating discussions about the future of a concrete area or place. [17] As a medium of co-production, RTD delivers design drawings synthesizing site observation, cartographic analysis and iterative stakeholder and expert inputs and feedback. RTD imaginaries take the role of 'open future explorations' guiding the commissioner in a complex thought- and transition process. [18]

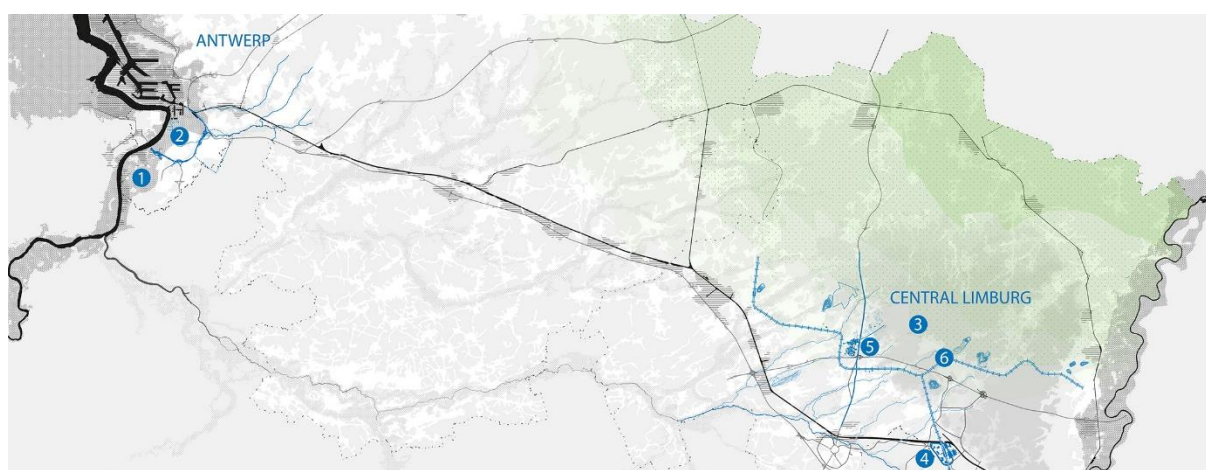
Acknowledging CE's multi-dimensional character the OVAM adopts RTD since 2014. In collaboration with different government agencies, OVAM commissions RTD to urban (landscape) design practices studying case-based regional metabolisms in projective forward looking ways. Furthermore, the OVAM and the Flemish Environmental Planning Agency (*Department Omgeving*), adopt RTD to define circular territorial development. Aiming to transcend merely technocratic accounting exercises on resource efficiency, these RTD studies investigate the potential reciprocity between transition to circular resource flows, densifying settlement patterns and initiating infrastructural synergies. [19]

### 1.4 Research objectives and methodology

This paper adopts comparative case study research, a common method in architectural research and the social sciences to study particular situations in depth and to narrow down broad research topics. [20] The case study research starts exploring, describing and explaining the selected cases' complexity and multiple facets in depth. [20,21]

It analyses six RTD studies on CE transition in Antwerp and Central Limburg, two Flemish areas transitioning to CE, executed between 2014 and 2017. The analysis feeds two research questions: articulating CE dimensions in space (part 3) and demonstrating RTD capacities in transition processes (part 4). Part 5 finally aims to clarify possible agendas for RTD in (CE) transition processes. Besides final RTD reports and policy documents, semi-structured interviews and a round table with both commissioners, urban (landscape) designers and researchers conducting the studied RTD [22] provide the analysis data.

## 2. SIX RTD STUDIES ON CE



**FIGURE 2.** Numbered case studies in Antwerp and Central Limburg (Northeast Flanders, Belgium).

The case study area is Northeast Flanders in Belgium. The Albert Canal ties together two regions in CE transition: Antwerp and Central Limburg.

Policy makers in both Antwerp and Central Limburg have attention for the potential reciprocity between CE transition, urban metabolism and restructuring space in a more sustainable way. In other words, they consider transition to more circular urban metabolisms in tandem with densifying settlement patterns and initiating infrastructural synergies. The first two projects are in the City of Antwerp. Antwerp has a strong RTD tradition supporting its high quality spatial policy. It has an in-house RTD department as well as a city chief architect guarding overall spatial quality. [23] The past few years CE enters as a theme in Antwerp RTD.

(1) The first RTD study is *Pilot Project Lage Weg* (Table 1.1) [24] (PPLW). PPLW imagines soil sanitation as an integrated phase in the redevelopment of a mixed industrial-housing area, proposing experimental collaborations across parcel and building owners. Reusing polluted lands being circular in itself prepares the ground for a circular productive site. PPLW adopts circular thinking on multiple levels: exchanging material flows, but also sharing spaces and resources between business owners and inhabitants. As such, PPLW incorporates economic, environmental, governmental, behavioural and societal dimensions in site-specific spatial proposals. (2) On the scale of the entire city Antwerp also investigates the city's metabolism (Table 1.2). RTD and mapping study *Metabolism of Antwerp* [25] (MA), aims to identify additional spatial development layers for Antwerp's spatial structure plan, striving for a healthier urban metabolism. [26] The study draws attention to resource flows impacting the city from the top-down, such as traffic and material flows linked to international trade via the harbour or the congested ring road. These flows extend city boundaries but highly impact the city's liveability: air pollution on the ring road but also in the narrow inner city 'street canyons' [25] is a major concern. Mapping air, water, heat and building materials networks, MA touches technological, governmental, economic and environmental dimensions related to Antwerp's metabolism.

The four following case studies are located in Central Limburg. This region undergoes economic restructuring with the closure of main regional employer Ford Genk in 2014. The Flemish Government launched here to an economic program, *SALK* [27], supporting Limburg

to transition to industry 4.0 and CE. Parallel to SALK, the Flemish spatial development department, RV, launched a territorial development program, *T.OP Limburg*, weaving together spatial development and the economic SALK agenda. Within *T.OP Limburg*, RTD plays a major role [28]. An initial RTD study in 2014 defined three thematic landscapes spatially translating existing and potential economic opportunities for Central Limburg [29]. Following this study, a series of RTD studies investigated spatial CE and renewable energy articulations in Central Limburg. *T.OP Limburg* advances the coal track, an abandoned railway track that used to serve the seven coal mining sites, as a crucial infrastructure to support Central Limburg's future circular material flows and practices. (3) Following scientific research on Central Limburg's deep geothermal energy potential to provide the area with sustainable energy [30], *Atelier Diepe geothermie* [31] (ADG) (Table 1.3) imagined how new geothermal heat infrastructures following and branching off the coal track could simultaneously restructure and densify the area's unsustainable spread out urbanization. Recycling the abandoned coal railway track as a carrier of residual heat, ADG mainly researched the integration of technological and environmental (urban densification) CE dimensions. (4) In 2016 the Flemish Government became owner of the 92ha large former Ford site in Genk. *Atelier Track Design* [32] (ATD) (Table 1.4) envisioned out-of-the-box design scenarios for a circular territorial redevelopment with Ford Genk as a regional catalyst. The design resulted in a phased redevelopment scenario proposing a flexible, incremental infrastructural landscape framework for resource exchanges, recycling the coal track as a carrier of regional resource flows such as heat, H<sub>2</sub> and water. A phasing diagram, indicating actors' potential roles in three phases building up to the reconversion of Ford Genk as a circular business park sheds a new light on circular industrial site reconversion. The design reframes actors' traditional roles and traditional linear development processes. ATD integrated aspects of governance, technology, connection to local jobs and initiatives (society) and landscape providing ecosystem services. (5) Genk's neighbouring municipality to the north, Houthalen-Helchteren (HH), pioneers in CE with a clean technology campus and the Remo-landfill innovating in recycling techniques such as enhanced landfill mining [13]. The emphasis of existing initiatives in HH being on technology, *Atelier #1 Houthalen-Helchteren* (AHH) [33] (Table 1.5) co-produced with stakeholders two visions integrating social and environmental dimensions in HH's CE. One positioned HH as a pioneer in sustainable mobility, the other scenario envisioned HH as a hub in a regional circular landscape economy. Both visions integrated community actors such as schools, as well as material flows with a lot of CE potential, such as biomass from landscape waste, excess water from mining subsidence areas, residual industrial heat. Another emphasis of 'circularity' was the integration of abandoned, underused and oversized infrastructures. (6) Finally, *Multiproductief Netwerk Kolenspoor* [34] (MNK) (Table 1.6) tested the coal track and adjacent vacant lands as an infrastructural carrier of small scale local food, energy and material practices and networks. It defined three development trajectories for the coal track in Genk: an experiential landscape park, a cycle machine and a production loop.

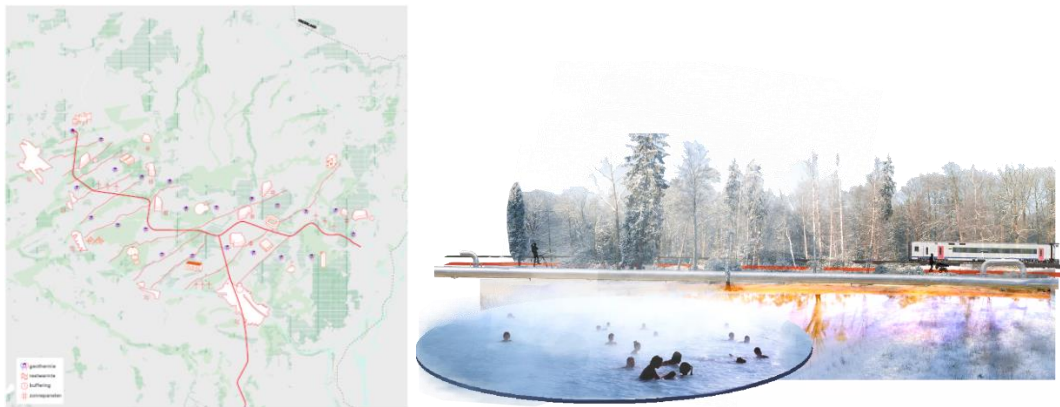
On one hand all the discussed studies interpret 'circularity' considering the territory itself as a resource. Besides material flows such as residual heat (ADG), biomass or water (AHH), the land itself (PPLW), abandoned, underused or oversized infrastructures (AHH), or the people using that land (MNK) are taken into consideration when designing circularity. The RTD studies adopt circularity as a lens to maximise resource reuse, sharing and synergies, with a careful contextual understanding.

### 3 ARTICULATING CE DIMENSIONS IN SPACE

The six RTD studies' forward looking design images spatially articulate place-based circularity interpretations. This section focuses on urban landscape design drawings as instruments integrating multiple CE dimensions.

#### 3.1 Multi-scalar material flow crosslinking

For material flows to be circularized, notions of sources and sinks require reconsideration. In CE, the source or material flow origin is the place where a waste flow is recovered. The sink is the place where the material flow is reused. ADG's and AHH's imaginaries (Figure 4) demonstrate circular territorial development locally crosslinking multi-scalar material flows. A regional heat network underneath an abandoned railway track recovers heat dissipating from the soil to the air from geothermal soil layers as well as residual heat produced by industries along the abandoned coal railway track (Figure 4 left). Combined with other recovered infrastructural waste flows, such as residual water from mining subsidence areas, new programs such as a heated public swimming pond along the coal track can be imagined (Figure 4 right). Depending on the needs, the residual water could also be reused by industries or natural areas along the railway. Figure 4's multi-scalar plan formats highlight the interplay between hard infrastructure and its surroundings. The heat network emerges as a landscape embedded infrastructure, combining heat distribution with recreation and productivity. Figure 4 shows the heat infrastructure side branches following river valleys, thus reinforcing historical urbanization patterns along the water bodies.



**FIGURE 3.** Regional heat network underneath former coal track (left: ADG) allows site specific programs, such as heated pools using excess water from mining subsidences in HH (right: AHH).

#### 3.2 The deep section

“Deep Urbanism is a reading of the city that acknowledges the complex ecological and biogeochemical processes taking place above, below and within the urban ground. In the city, nothing can simply be placed on the surface; the composition of the urban ground requires that structures inevitably extend deep into a complex mix of disturbed soil horizons, construction rubble, pipes, subways, utilities.” [35]



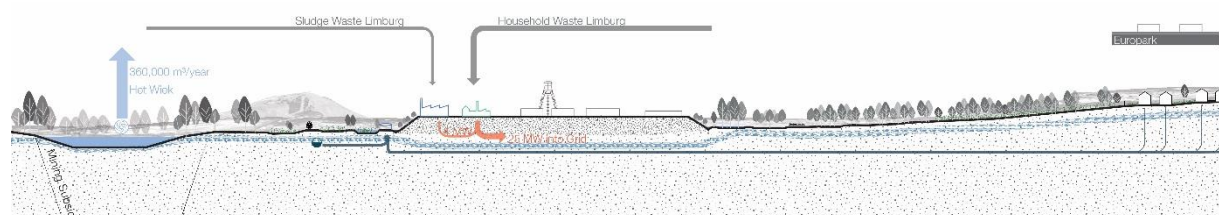
Figure 3's deep sections for ADG and AHH spatially articulate potential interplays between technology, public space and productivity related to a new regional heat network. The roll-out of this residual heat network creates opportunities to introduce new programs such as greenhouses, heated bicycle lanes or swimming ponds (Figure 3 and 4). The deep sections articulate interdependencies between heat flows and spatial programming above and below ground in integrated infrastructural systems supporting circularity [36].



**FIGURE 4.** Designing new programs in synergy with a new regional heat network. (left: ADG, right: AHH)

### 3.3 The transect: a synoptic view of human land occupation and exploitation

Indebted to Von Humboldt's eighteenth and nineteenth century transects across South America, transects offer open formats synthesizing interconnectedness and complex coherences of ecological systems in one image. [37] Similarly, transects such as AHH's Figure 5 articulate spatial coherences and disruptions between natural and man-made systems concerning material flows. Figure 5 shows an industrial platform on a flattened former coal mining slag heap, receiving Limburg's household waste as well as its waste water and the region's water treatment plants' sludge. A waste incinerator delivers heat to a sludge drying facility transforming the sludge into a building material component. As a consequence of subterranean coal extraction, entire areas have sunk up to twelve meters and are flooded by ground water. Derived from Sankey diagrams typically representing Material Flow Analysis in industrial ecology, Figure 5's arrows anchor data about natural resource colonization and material flows to space. This trans scalar understanding of the site supports a contextualized CE approach, identifying existing yet undefined and currently isolated linear waste flows that could be integrated in a place-based circular redevelopment.

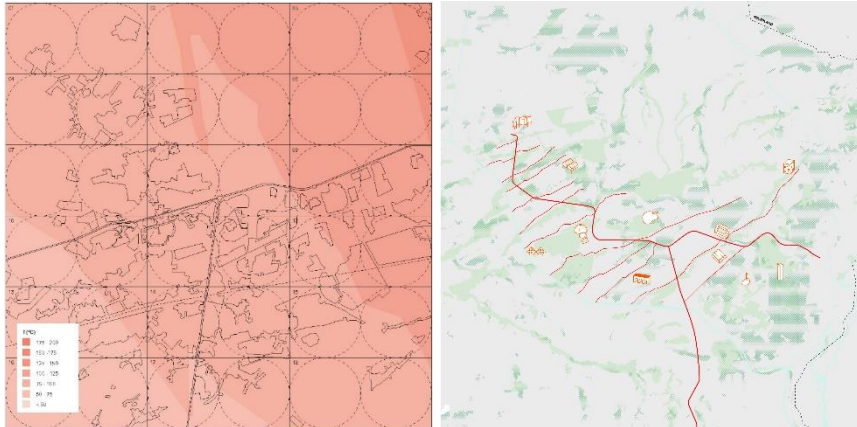


**FIGURE 5.** Houthalen-Helchteren transect articulating material flows and space dependencies above and below ground. [30]



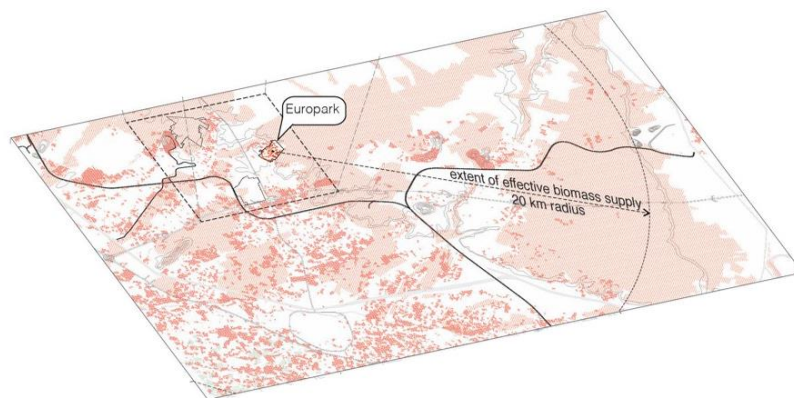
### 3.4 Material sheds: defining new forms of territoriality

Circular material flows define new material sheds, meaning new trajectories from source to sink and other agents, infrastructures, conditions and tendencies supporting them. For example, deep geothermal energy can only be transported over 6 km after extraction. Following this technical parameter, ADG defined two possible infrastructure typologies driving fundamentally different spatial configurations: 'heat islands' and 'heat networks' as shown in Figure 6.



**FIGURE 6.** Heat sheds: heat islands (left) and heat network (right) depending on specific spatial conditions for geothermal heat networks in ADG.

AHH's biomass recovered from landscape management waste, has an operational radius of twenty kilometres from the biomass collection point. This distance limit guarantees a carbon neutral logistical chain for biomass landscape waste collection and its redistribution as raw material. [38]



**FIGURE 7.** Biomass shed in Houthalen-Helchteren's biomass hub (AHH).

### 3.5 Recombining plan forms and design formats interpreting CE as an ecological territorial approach.

Spatial representations appear to be very helpful to start imagining place specific multi-dimensional CE transitions. They act as visual synoptic instruments, synthesising how multiple CE dimensions could merge in space. Unlike traditional masterplans proposing fixed 'solutions' in space, the discussed design instruments pin down essential elements in space. Their open-endedness nurtures open conversations and absorbs insights on what 'could'

happen. The projective images' accessible and attractive capacity, break through the status quo. Using them in a co-productive way, they act as mediators between experts and stakeholders, offering tangible and accessible spatial representations in often abstract conversations about CE dimensions. The studied imaginaries each represent synoptic views integrating technological, governmental, societal, behavioural, economic and/or environmental dimensions. Depending on the specific research question, the design teams integrated expertise from different sectors when developing circular spatial scenarios. For example, ADG (Table 1.1) bridged infrastructural engineers with planners and designers. AHH involved ecologists, community representatives, industry and policy makers (Table 1.3) and MNK (Table 1.6) strongly connected community groups with planners and the local policy makers. ATD (Table 1.4) proposed an alternative industrial redevelopment scheme, anchored in ecological networks and anticipating new policy frameworks, circular science, market and technology innovations.

## 4. RTD MEDIATING TRANSITION PROCESSES

### 4.1 Process supporting study results

As discussed in the previous section, each of the six RTD studies produced spatial articulations of possible circular futures. Transition to CE still being in an early stage, implementation of these imaginaries would simultaneously depend on new stakeholder coalitions and reformulated policy frameworks. Rather than being directly implementable, the imaginaries serve as one step in a long process of defining how a multi-dimensional CE could be realized. In this light it is interesting to investigate which results the six RTD studies obtained in the transition processes themselves. Since these results (listed in Table 1 column 4) are mostly process-supporting, they are hard to identify, let alone to be proven. Interviews with the design offices who executed the RTD studies, as well as the leading commissioners nevertheless provided the insights listed in Table 1. [22]

(1) In Antwerp's *PPLW* (Table 1.1) the iterative design process concluded with land owners signing an engagement declaration for an integrated, experimental and collaborative area redevelopment and soil sanitation. Different urban design formats supported specific co-production processes clarifying the issues and opportunities, triggering stakeholder engagement and ownership. For example, individual site owners were taken on a site safari with a brochure visualising possible futures as a result of collaborative soil sanitation and site development, sharing spaces and resources. Simultaneously, the design team 51N4E noted a new consensus about mixed land uses within the administration, seemingly nurtured by the design process.

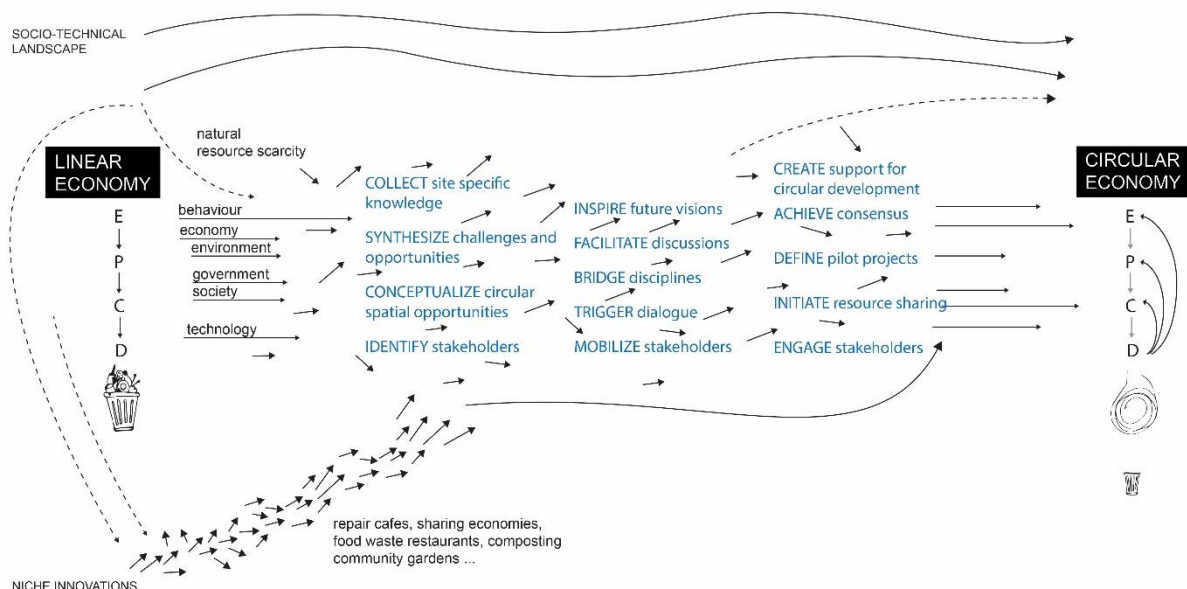
(2) Identifying and mapping enormous stakeholder networks related to water, energy, air and construction materials, the *Metabolism of Antwerp* (Table 1.2) simultaneously mobilized and engaged these formerly disparate stakeholders. Throughout the study, the design team also initiated online data collection and sharing platforms supporting and accelerating exchanges between all relevant parties [39].

(3) *ADG* (Table 1.3) adopted design to bridge engineers, planners and designers. A graphical synthesis of technical data continues to support multidisciplinary exchange on the topic. (4) In *ATD* (Table 1.4) future design scenarios for a circular industry site facilitated delicate

conversations about ambition levels between different government agencies. Where the economic department was mainly interested in generating jobs as soon as possible, the design scenarios made the case for a contextualized, experimental and slower development process. (5) *Atelier HH* (Table 1.5) initiated an ongoing investment by the municipality in design research, with successful applications for a RTD government subsidy defining an implementable pilot project for integrated soil sanitation and development of a circular business park [40]. (6) Finally, *MNK* (Table 1.6) mobilised and connected existing stakeholders and enabled defining a number of pilot projects for the coal track as a backbone for a CE embedded in existing social and productive networks.

## 4.2 RTD supporting pathways to CE

This paper's case study research indicates that future imaginaries co-produced with stakeholders and experts supported pathways to CE transition in Antwerp and Central Limburg. The mostly intangible process supporting study results discussed in 5.1 could be crucial stepping stones in the transition process, supporting the necessary recalibration of transition dimensions [39]. As listed in 5.1, RTD triggered dialogue, creativity, doubt and conflict in co-productive design, achieved consensus and engagement for integrated development, identified, mobilized, connected and engaged stakeholders, initiated shared data collection, bridged multidisciplinary teams, facilitated conversations, inspired and supported municipalities and defined pilot projects. These results are integrated in Figure 8's transition scheme, articulating RTD's potential roles supporting transition pathways from linear to CE.



**FIGURE 8.** Possible roles of RTD in transition to CE by author. Source: diagram by author based on Geels 2007 p. 401 [11] Pomponi and Moncaster [2] and EMF [4]

Table 1 summarizes the application of RTD for both study case areas: column 2 synthesizes the research question related to circular economy, column 3 lists the design output articulating potential circular futures and column 4 lists RTD process-results.

**TABLE 1.** Summary of six RTD studies articulating CE dimensions.

	RTD STUDY	RTD QUESTIONS RELATED TO CIRCULAR ECONOMY	DESIGN OUTPUT	OTHER STUDY RESULTS
	<b>ANTWERP</b>			
1	Pilootproject Lage Weg (PPLW) 2015-2016 [24] <i>Commissioned by: stad Antwerpen stadsontwikkeling, Kenniscentrum Vlaamse Steden, OVAM</i> <i>Executed by: 51N4E, Connect &amp; Transform</i>	Inserting circular logics in the redevelopment of a partially abandoned housing and industrial area. Reusing polluted lands for circular production.	Bird's eye perspectives, physical site model, photomontages and disposable masterplans reframing and clarifying the redevelopment issues and opportunities at stake.	Specific co-productive design formats triggering dialogue, creativity, doubt and conflict  Land Owners signed Engagement Declaration for integrated redevelopment  Consensus about mixed land uses reached within administration
2	Metabolisme van Antwerpen, stad van stromen 2017-2018 (MA) [25] <i>Commissioned by: City of Antwerp, the Flemish Spatial Department, de OVAM and the port of Antwerp</i> <i>Executed by: Fabric i.s.m. Marco Broekman, UAntwerpen, Common Ground.</i>	Mapping Antwerp's urban metabolism flows to support the Antwerp Strategic Spatial Structure Plan update	'Bluecards' identifying opportunities to evolve to a circular city with sustainable material flow management	Stakeholder identification and engagement related to each flow  Initiating a data collection and sharing platform amongst stakeholders
	<b>CENTRAL LIMBURG</b>			
3	Atelier diepe geothermie 2015-2016 (ADG) [31] <i>Commissioned by:</i>	Imagining how a new energy infrastructure can restructure	Graphical technical data synthesis supporting	Bridging technological, contextual and spatial

	LABO RUIMTE (RV & Team Vlaams Bouwmeester), VITO <i>Executed by: 51N4E</i>	regional urban sprawl.	multidisciplinary use  Maps, diagrams, photomontages, deep sections for two area specific infrastructure typologies supporting densification	parameters and associated experts and stakeholders
4	Atelier Track Design (ATD) 2015-2016 [32] <i>Commissioned by: Ruimte Vlaanderen, OVAM</i> <i>Executed by: WIT Architecten, OSA KU Leuven, Lateral Thinking Factory, Technum Hasselt</i>	Out-of-the box design scenarios for a circular redevelopment for Ford Genk as a hub in a circular Central Limburg	Phased multi-scalar plans, deep sections, transects, process and stakeholder diagrams for setting up a flexible context-based infrastructural framework for exchanging resources	Facilitating conversations about ambition levels around 'circularity' between different government agencies
5	Atelier #1 Houthalen-Helchteren 2016 (AHH) [33] <i>Commissioned by: Ruimte Vlaanderen, Houthalen-Helchteren</i> <i>Executed by: OSA KU Leuven, DASTU/Politecnico di Milano</i> <i>Invited stakeholders/experts: RLLK, Space Caviar &amp; Z33, RxD KUL (Alvin&amp;Andrew), Remo Landfill, Limburgs Landschap vzw</i>	Envisioning a social and ecological context-based transition to CE in Houthalen-Helchteren	Phased multiscalar plans, deep sections, transects, process and stakeholder diagrams for two future visions for Houthalen-Helchteren	Inspiring municipality to think across sectors and administrative borders, to see opportunities instead of issues  Supporting funding application for follow-up research
6	Multiproductief Netwerk Kolenspoor 2016 (MNK) [34]	Testing the coal track as an infrastructural carrier of small scale food,	Interactive site model,  Defining three trajectories for	Mobilizing and connecting stakeholders

	<i>Commissioned by:</i> <i>Stad Genk and Thuis in de Stad</i> <i>Executed by:</i> <i>Plusoffice Architects,</i> <i>Delva Landscape Architects,</i> <i>Living Lab de Andere Markt</i>	energy and material practices and networks	the coal track in Genk (experiential landscape park, cycle machine, production loop)	Defining pilot projects
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## 5. CONCLUSIONS

### 5.1 Urban landscape design capacities: form and process

This paper firstly unpacked how multiple CE dimensions found a repository in shared graphic representations that are fundamentally place-based and spatial. Urban design formats such as the transect and the deep section offer graphic spatial synopses of multi-scalar and multidimensional contextual parameters. Unlike traditional masterplans, the discussed spatial imaginaries are not to be understood as one on one solutions. They are rather open design instruments capturing issues and opportunities at stake in specific spatial contexts, acknowledging the impossibility to generate one-fits-all solutions in complex reality. Sketching opportunities of the territory's resourcefulness, they open imagination and serve as media to learn collectively across disciplines and government silos about the complex unknown circular future. Breaking open imagination, they hold a tremendous potential to take up a mediating role in transition processes.

Secondly, the paper articulated such possible mediating roles for RTD to support or accelerate CE transition. In the six case studies, the imaginaries helped formulating clear questions and problem statements around CE's (potential) spatial articulations. Urban design drawings served as media supporting cross sectoral conversations about CE. The research indicates that the RTD method has the potential to integrate different social groups, CE scales and models and ecological challenges while connecting spatial development to sustainable and resilient economic redevelopment.

The case studies developed in this paper demonstrate several ways in which urban (landscape) designers could contribute to complex transition processes. With their integrative and coordinating mind-sets and visual instruments, urban landscape designers can support switching from single sector approaches to understanding dependencies between them. Urban landscape designers' synoptic methods and capacities could be useful in reframing CE's multidimensionality questions as essentially site-specific spatial questions. RTD could take up an integrating role throughout the entire transition process. Therefore this research recommends involving urban landscape designers from the very beginning to help identifying and formulating place-based circular economies. RTD's application in transition processes can help defining qualitative frameworks that can gradually integrate quantitative assessments, rather than the other way around.

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## 7. A METHODOLOGICAL PROPOSAL TO EVALUATE THE ENVIRONMENTAL FOOTPRINT OF CITIES

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**ABSTRACT.** For the first time in human history, more than 1 person out of 2 is living in urban area and projections talk about a further increase up to 66% of human global population by 2050. As cities concentrate also most of the world's economic activities, this convergence of human and economic capital could lead to higher pressures on planet Earth in terms of environmental impacts, if not properly addressed. Holistic methodologies are necessary to understand, manage and tackle environmental pressures of urban contexts, avoiding the risk of burdens shifting both spatially and temporally. The assessment of environmental impacts and performances are usually conducted from two perspectives: top-down (e.g. Urban Metabolism) and bottom-up (e.g. Life Cycle Assessment) approaches. The purposes of this contribution are: i) presenting the current state-of-art in terms of urban environmental impact assessment and ii) proposing the City Environmental Footprint, a new methodological approach to evaluate the environmental footprint of cities in a comprehensive way.

**Keywords:** Urban Environmental Impact Assessment; Urban Sustainability; City Environmental Footprint; Urban Metabolism; Life Cycle Assessment

### 1. ENVIRONMENT ASSESSMENT OF THE URBAN CONTEXT: OVERVIEW AND STATE OF ART

For the first time in human history, more than one person out of two is living in urban areas. Projections say that cities will continue to grow and be a pole of aggregation for human beings, especially in developing countries, with 66 per cent of human global population residing in urban areas by 2050 [1]. Many drivers are responsible for this phenomenon, e.g. the intersection between supply and offer of jobs and services, better and safer living conditions, or even a higher attractiveness in terms of social lifestyles and opportunities.

Cities are complex and dense systems, they require great amounts of energy and material and they often produce huge amounts of waste in order to sustain such intensive living activity. This means that the subsequent environmental burdens are high and they are likely going to be higher in the future, if the urban population will increase at this pace. The density of social and economic capital of cities makes them complex and evolving systems that require huge amounts of energy and materials to survive and that are responsible for important environmental burdens. Indeed, even if cities account for about 3% of the world surface, they are responsible for 60-80% of energy consumption and 75% of greenhouse gas emissions [2]. Nevertheless, the concentration of natural and human capital gives also the opportunity to cities to be drivers for change and to address more favourably the impacts on planet Earth:

the solutions towards a more sustainable transition of our society are likely to be found in city life.

The importance of cities in this transition was recognised also by United Nations, with the 17 Sustainable Development Goals (SDGs). The 11th goal is explicitly addressed to cities, and aims to “make cities inclusive, safe, resilient and sustainable” [3].

How to reach such ambitious targets is still an open issue, as cities represent the most complex system ever created by man. Cities widely differ in terms of size, context, social and economic patterns, historical development, etc. and this means that a single definition of “city” does not exist yet, but many definitions are possible according to the focus and targets of research. In this regard, making “the city” as object of assessment is not a trivial task: issues related to an appropriate definition and system boundaries are still open and object of debate. Such complexity makes the application of holistic methodologies necessary to understand, manage and tackle environmental pressures of urban contexts, avoiding the risk of burdens shifting both spatially and temporally. Unfortunately, these are still lacking at the urban level and the methodologies currently available present both strong and working points (Figure 1). To date, the assessment of environmental performances are usually conducted from two perspectives: top-down and bottom-up approaches [4]. Top-down approaches are systematically complete in depicting the interactions between economic sectors (Input-Output Analysis, IOA) and urban areas and surrounding natural environments (UM, Urban Metabolism). The UM concept and related methodologies (such as the Material and Energy Flow Analysis) allow making an inventory of the direct flows of materials, energy and waste into and out of the city, but it do not allow to include the flows coming from upstream and downstream processes and interpret these flows in terms of environmental impacts, providing only an assessment of the environmental performances. The Environmental Input-Output methodology attempts to estimating environmental impacts through the analysis economic flows, but it is often available only at national or regional scale. The application to the urban context is subjected to assumptions with a high degree of uncertainty and poses then some threats for the quality of the results.

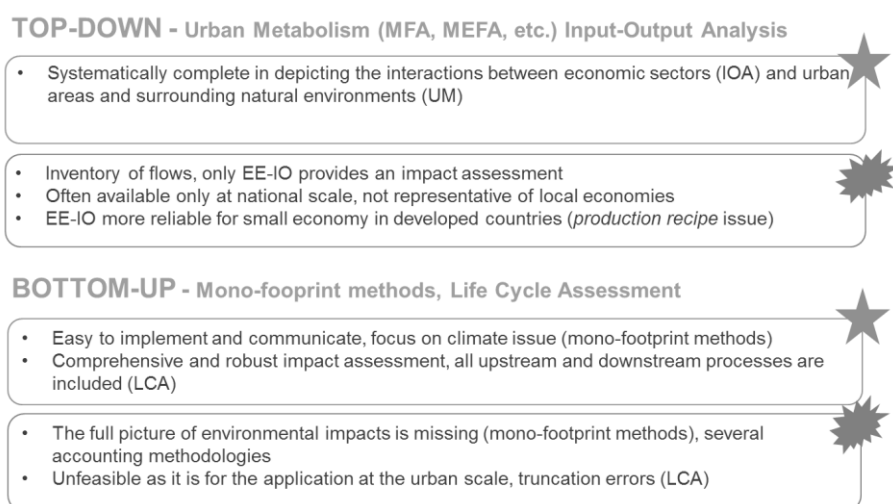
Regarding the bottom-up approaches, Carbon Footprint and Water Footprint are the most widely used methods to evaluate the environmental performance of cities to date, despite their limited scope. Several points have made these methods appealing to policy makers and organizations: i) political commitments at national and international level; ii) rise of consensus and concerns related to climate change and water scarcity; iii) relatively easy implementation and communication of results. Notwithstanding, shortcomings are present. As these methods focus only on one single environmental impact or issue, a comprehensive picture is missing and the risk of burdens shifting could be high [5, 6] Furthermore, the proliferation of schemes and approaches raised and the differences inherent to the urban contexts combined with the lack of a single standardized method, make the interpretation of results often difficult to analyse and compare.

Finally, Life Cycle Assessment (LCA) and Life Cycle Think approach (LCT) may be considered the most comprehensive and robust holistic methodology to face this challenge. Compared to the other methodologies presented, LCA has numerous advantages. Firstly, LCA takes into account all processes, including upstream and downstream, from a cradle to grave perspective, i.e. from the extraction of raw materials necessary, to the production, use and final disposal (e.g. not direct operational energy use in a building for example, but also embodied impacts related to the materials used). Furthermore, LCA considers a wide range of environmental impacts (up to 18) and it is able to effectively compare the effects of different scenarios (e.g. business as usual versus innovative scenario). The risk of burdens-shifting

from one environmental impact to another is drastically reduced, compared to other methodologies. For instance, in case of application to the urban context, the impacts and benefits associated with two or more transportation and/or waste management scenarios could be evaluated and compared. Furthermore, hotspots and drivers of such identified environmental impacts can be precisely detected and investigated, leading to more precise and consciously interventions and proposals at policy level.

Even if LCA was born as product-oriented, recent proposals have been made to broaden its object of analysis by studying larger scale systems [7], that could even take into account the surrounding context and potential rebound effects [8]. The increasing attention towards this topic by the scientific community and policy makers is leading to an increasing number of LCA case studies implemented to the system/infrastructure level [9]. Nevertheless, the application of LCA to the whole urban scale is not a reality yet. Many constraints make its application to the urban context still unfeasible. Indeed, its current application is limited in scope (specific urban sub-sectors, such as waste management or wastewater treatments, etc), or assessment (few impact categories are evaluated). Furthermore, other methodological gaps are found and are still unsolved for a wide application of the methodology to urban systems, namely: i) definition of system boundaries; ii) definition of an appropriate functional unit and function of the system; iii) complex and time-consuming data gathering; iv) resolution and importance of an appropriate impact assessment.

Therefore, the main objectives of this contribution are to provide insights in a selection of available methods and current urban LCA applications to identify strong and working points, as well as methodological challenges. Successively, a proposal for new methodological advancements is presented, namely City Environmental Footprint, to overcome the current gaps.



**FIGURE 1.** Critical comparison between top-down and bottom-up methodologies: the stars mark the good points, the jagged balloon the working points

## 2. MATERIALS AND METHODS

### 2.1 Investigation and comparison of selected methodologies for environmental assessment

As stated in the introduction, the rise of scientific consensus on human-induced climate change and the urgency to take actions against it have recently led to a proliferation of standards and Carbon Footprint methods. Such proliferation of methods is, however, not always fruitful, but rather confusing. A standardized method is lacking to date and systemizing different approaches remains a challenging task, as no international consensus exists. Moreover, various problems encounter when trying to implement the various methods, ranging from issues related to the definition of system boundaries, to the type, source, amount and quality of available data, as well as to the allocation procedures. The heterogeneity of reporting and verification steps across the various accounting schemes create additional problems. In this context, political claims such as “climate neutral” targets can be misleading and even erroneous, and they can lose their efficacy and power towards society.

Then, the first aim of this contribution is to explore in-depth the theoretical and practical issues with the support of a critical analysis focused on a set of selected methodologies currently available at city level, namely the Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC) [10], Bilan Carbon [11], and ISO/TS 14067:2013 [12], including a comparison with the Organizational Environmental Footprint (OEF) [9]. The latter is an environmental multi-criteria assessment methodology intended for high-scale and complex systems based on LCT with a high level of accuracy and comprehensiveness. In this critical analysis special attention is paid to the definition of the urban context and the related system boundaries, data gathering and data quality, and allocation procedures, especially the ones related to dynamic fluxes (e.g. production/consumption based approach, transportation). Final considerations are dedicated to reporting and communication issues. The selected methodologies were critically analysed in order to identify their most important features considering LCA as a reference methodology and urban context as the system under study. These features are: i) applicability to urban context; ii) type of approach; iii) application of LCT principles; iv) Impact Assessment; v) Functional Unit considered; vi) System Boundaries; vii) Inventory data; viii) Data Quality; ix) Allocation Rules x) Identification of responsible actors; xi) Verification; xii) Ancillary tools.

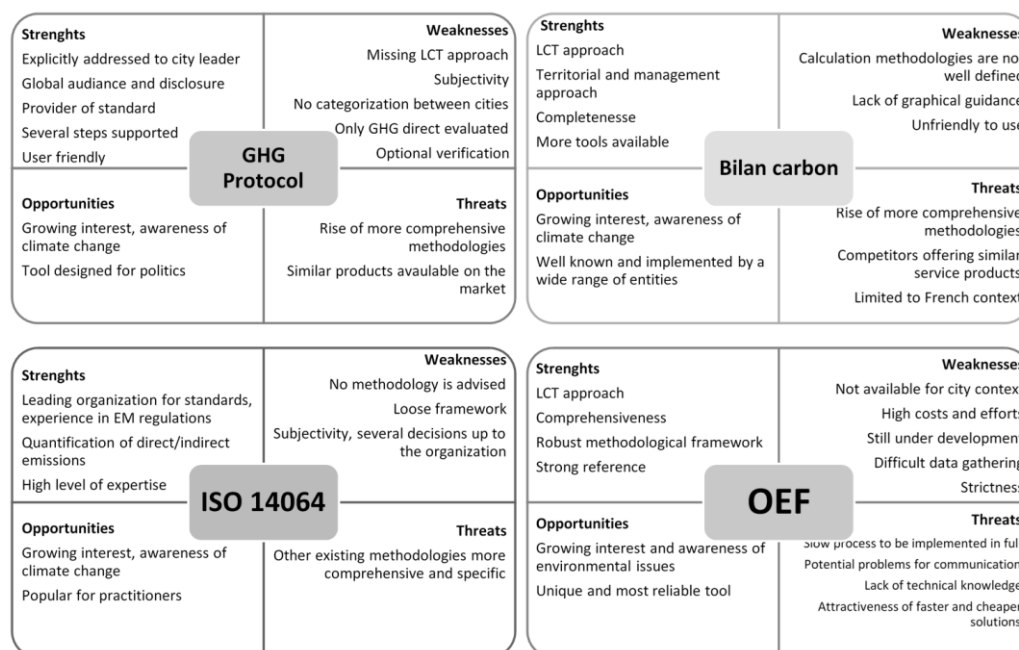
The results of the critical comparison are displayed in Table 1.

**TABLE 1.** Critical comparison of a selected set of methodologies: Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC), Bilan Carbon, and ISO/TS 14067, Organizational Environmental Footprint (OEF) – Selection of most relevant features and results

Key Feature	GPC	Bilan Carbone	ISO 14064	OEF
Availability at city level	Yes	Yes	No	No
LCT	No	Yes	No	Yes
Impact assessment	Climate Change, GHGs included in Kyoto Protocol	Climate Change, all GHGs emissions	Climate Change, significant GHGs	A default set of 14 mid-point impact

		according to the present level of scientific knowledge	emissions for the Organization	categories and specified impact assessment models with according impact indicators (for Climate Change IPCC 2007, 100yr)
Functional unit	Not addressed explicitly, supporting information refer to emissions related to the yearly city performance	Not addressed explicitly	Not addressed explicitly	Yes
System boundaries	Territorial boundaries, Flexible, depending on purpose	Territorial or administrative boundaries	Operational or Organizational boundaries, control or equity share approach	Fixed, all activities and processes which occur within the Organizational boundaries
Inventory data	Activity data, national or international statistics; equations are provided. Two levels of accounting	Activity data, national or international statistics	Activity data or direct measurement. No quantification methodology specified	Specific sector data or best available generic data for data gaps. Data management plan provided
Approach	Territorial/Production approach + supply chain	Life Cycle	Production approach + Supply Chain limited to electricity. Other indirect emissions optional	Life cycle, cradle-to-grave
Identification of responsible actors	Yes, but limited in scope; influenced by inventory rules	Yes; influenced by inventory rules	Yes, but limited in scope; influenced by inventory rules	Yes
Verification	On a voluntary basis, self-verification or third party verification allowed	No precise guidelines	Guidance for internal and external verification	Compulsory, third-party review

Afterwards, each method was screened highlighting strong points and shortcomings through a SWOT analysis (Figure 2).



**FIGURE 2.** SWOT analysis, good and working points of GHG Protocol, Bilan Carbon, ISO 14064 and OEF for application to the urban context

The analysis of the key features, strong and working points presented highlights points for comparison and reflections for each method. According to the analysis and the reference to the OEF, the Bilan Carbon performs better with regard to the target of an efficacious GHG emission accounting at the urban level for a number of reasons. First of all, it is designed for cities and utilizes an LCT approach for every sector considered, including all direct and indirect emissions also from upstream and downstream processes. Furthermore, it is particularly effective to balance the academic research and the policy-demand and it includes a comprehensive accounting of GHG emissions, as this is not limited to the ones included in the scope of the Kyoto Protocol, the good guidance to the user from the methodological point of view and the supply of supporting material, as the spreadsheets for emissions factors.

Despite this promising features, Bilan Carbone requires higher costs of implementation that shall be taken into account at policy-level, due to: i) big and time-consuming life cycle data gathering; ii) the level of expertise necessary to manage it and to apply the method, as the guide is less user-friendly than the GPC Protocol. Finally, reporting and verification are not in the scope of the method, despite their importance for communication purposes to the stakeholders and to ensure the reliability of the results.

The analysis undertaken for the GPC recognizes its user-friendly approach tailored for cities and policy-makers, the attempt to follow IPCCs recommendations from the municipal perspective, its degree of flexibility that can encourage interested neophytes in participating to the climate discussion. However, the major scope of the standard is inventorying direct territorial GHG emissions, this could lead to an underestimation of consumption-based emissions and increase the risk of burdens shifting to other territories. At top of this, accounting guidelines are found to be loose and this can affect the quality of results and the

purpose of comparison between cities and target-oriented strategies. Verification and reporting are only encouraged and guidelines are not provided.

On top of the considerations provided above for Bilan Carbone and the GPC, the ISO 14064 benefits from its standard-oriented and loose framework that could be attractive, but that does not seem enough comprehensive for the challenge of urban emissions accounting, as no precise indications neither on GHG to be accounted for nor on the quantification methodology are provided. Direct and (partially indirect) emissions are inventoried, but key choices are in charge of the organization. Anyway, reporting and verification procedures are well developed and defined.

Finally, it is remarkable to summarize some of the most important features of the OEF that make it eligible to be used as reference methodology and should be taken into account from experts and municipal stakeholders for improvements of reliability, consistency and transparency of urban-related GHG emissions accounting, and, on a later stage, for the assessment of environmental impacts.

The OEF method applies to organizational activities as a whole – in other words, to all activities associated with the goods and/or services an organization uses and provides from a life-cycle perspective. Depending on the use and purpose of the OEF study, the key requirements are different. This allows flexibility and optimization of the efforts and it is an important issue to be investigated also from the city requirements point of view. This, however, does not imply an excessive subjectivity as in the case of GPC or ISO 14064. Indeed, the guidelines are very similar to the LCA methodology, but stricter and more complete.

As a general conclusion, it is important to remark that no method provides an in-depth discussion and proposal about the challenge of defining and categorizing the urban system in an appropriate way to serve a more efficient assessment.

## **2.2 Current LCA applications at the urban scale: analysis of existing constraints, patterns and trends**

As second part of research related to the current state of art, a review study was carried out, taking into account the published literature from 2010 to the present [13]. The aim is twofold: i) acquiring a comprehensive overview of the current applications of LCA at the urban level; ii) defining a potential research agenda to make LCA suitable for urban studies.

Whereas a direct application of the methodology to the full urban scale does not exist yet, an analysis for the different urban sub-systems was carried out. The sub-systems identified are: i) built environment; ii) energy systems; iii) waste; vi) water; v) consumption patterns; vi) transportation networks; vii) urban open spaces and green (including aspects related to land use and ecosystem services). The intention is to cover the majority of the urban activities needed to sustain the “life” of the city itself and its inhabitants, in terms of citizens, residents and visitors (commuters, tourists, etc.), services, etc. Two additional core topics were covered: i) hybrid approaches, i.e. combination of LCA with top-down methodologies (e.g. under the UM umbrella) and/or with other tools used in the urban planning and management, such as geographical information systems (GIS) and remote sensing; ii) upscaling LCA from urban sub-systems to the upper scale level. The relevant papers were selected based on two criteria: i) the papers shall deal with full LCAs, i.e. including a wide range of impact categories; ii) and the case studies for the urban sub-sectors shall be considered at the whole urban scale. Few exceptions to these criteria were allowed, e.g. evident elements of novelty, support to urban planning, etc.

In the screening phase almost one thousands of titles and abstract were analysed and a shortlist of 65 papers was selected. The analysis of the selected literature confirmed that no applications of LCA at the full urban scale exist to date, while upscaling approaches are still on their way of development. Waste and water sub-sectors seem to be the most mature in performing the transition from the product/process level to the higher scale systems and LCA is found to be used mainly as supporting tool for policy making, and strategic and comparative analysis. In terms of literature coverage, the transportation sector and energy systems follow, but for these the impact assessment is mainly focused on assessing and comparing emissions and energy demands or technology systems, respectively. For what concerns household consumption and urban building stock, the topic is poorly explored or still unexplored in an integrated way, despite its relevance.

The attempts of upscaling approaches are still limited in their scope and practices, and even the use of hybrid methodologies is not usually applied at the entire urban level. The most comprehensive and established framework is found to be the territorial LCA [7, 14], while other upscaling approaches are applied to a limited spatial extent, e.g. neighbourhood scale, or they focus on specific urban issues [15]. Finally, it is interesting to notice that there is a claim for integration of LCA with spatial planning and ICT tools, due their potential for data gathering and management, spatialization of impacts and visualization purposes.

In the second part of this review study current bottlenecks for LCA at urban level were screened and discussed [7]. More specifically the following issues were reviewed in more detail: i) System Boundaries; ii) Functional Unit; iii) Data granularity and quality; iv) Life Cycle Impact Assessment. These four elements are crucial for the correct application of LCA methodology and are here briefly presented.

The system boundaries define the borders and bounds of the analysis, determining which unit processes shall be included and excluded in the study. Depending on the goal and scope of the study, the system boundaries are also influenced by the perspective taken, i.e. territorial/production (activities in the territory) or consumption approach (including activities outside the territory but related to consumption dynamics in the territory), in the case of urban context and GHG emissions.

The Functional Unit (FU) is a concept typically related to LCT, it defines the reference unit of the study for the inventoried flows and it allows for comparison. Typical FUs for the urban context are the entire city over 1 year or one single citizen over 1 year (e.g. kiloton of CO<sub>2</sub>eq per year or CO<sub>2</sub>eq per year\*capita, respectively).

As pointed in section 1, there is no unique agreement on the definition of a city and its system boundaries. As a unique definition of “city” does not exist yet, it is questionable and object of debate what could be an appropriate choice to evaluate such a heterogeneous and dynamic system as the urban context.

Data granularity and their quality are of paramount relevance for the purpose of the appropriate and precise identification of the responsible actors, in order to avoid the black box approach of UM.

The Life Cycle Impact Assessment phase aims at translating the inventory flows in potential environmental impacts with the support of specific models (impact assessment methods). According to the methods and impact categories selected is possible to evaluate up to 18 different environmental impacts, e.g. human toxicity, eutrophication, resource depletion, etc. besides the popular climate change.



The analysis of the papers selected revealed that only upscaling approaches discuss and try to overcome the current bottlenecks that remain open issues and methodological gaps to solve [7, 13, 14, 15].

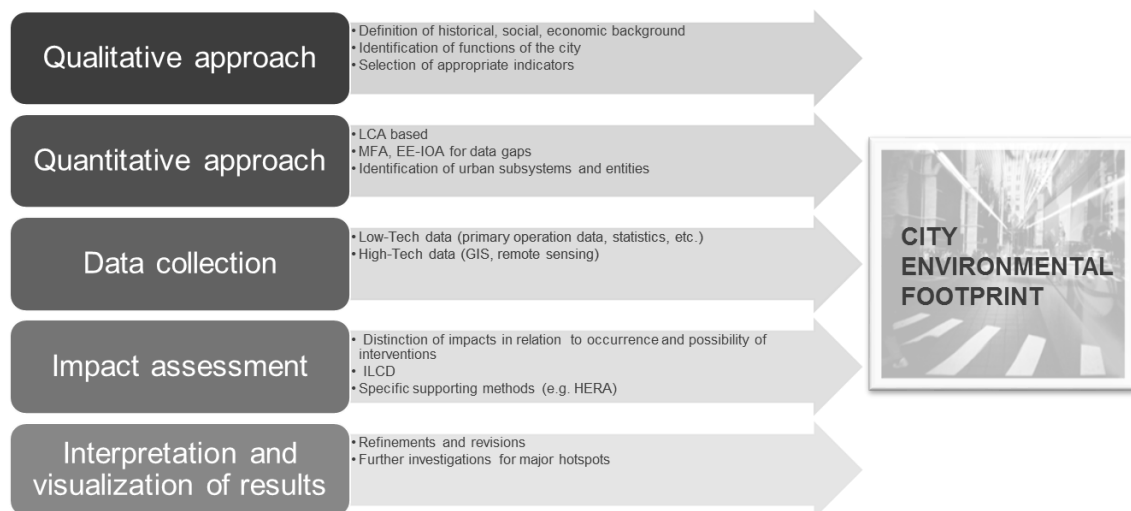
The key conclusion emerged from the review confirmed that LCA is a raising and promising methodology to assess the environmental impacts of cities in a holistic way, but further adjustments and improvements to the methodology are needed [13].

### 3. THE CITY ENVIRONMENTAL FOOTPRINT: PROPOSAL FOR A NEW METHODOLOGICAL APPROACH TO EVALUATE THE URBAN ENVIRONMENTAL FOOTPRINT

The outcomes of the previous steps served as a basis for the proposal for a City Environmental Footprint (City EF), a hybrid methodology, LCA-based, able to combine top-down and bottom-up approaches, to overcome the current limitations existing in the field of urban environmental assessment.

Top-down methodologies enable to identify the main fluxes going into and out of the city (i.e. typically inventoried for the main sectors within a city). Bottom-up approaches allow for microscale analyses of various sub-systems of the city (e.g. residential buildings, infrastructure, transport, energy production, water supply, etc.) and their constituting processes and/or products (e.g. construction products, use of appliances, heating energy use, cooling energy use, etc.). The first simplify the data gathering process and/or fill data gaps. The combination of both approaches with a different level of granularity results in a more precise and detailed modelling and data inventory and allows for a more clear identification of hotspots and opportunities for efficient and effective improvement of the city.

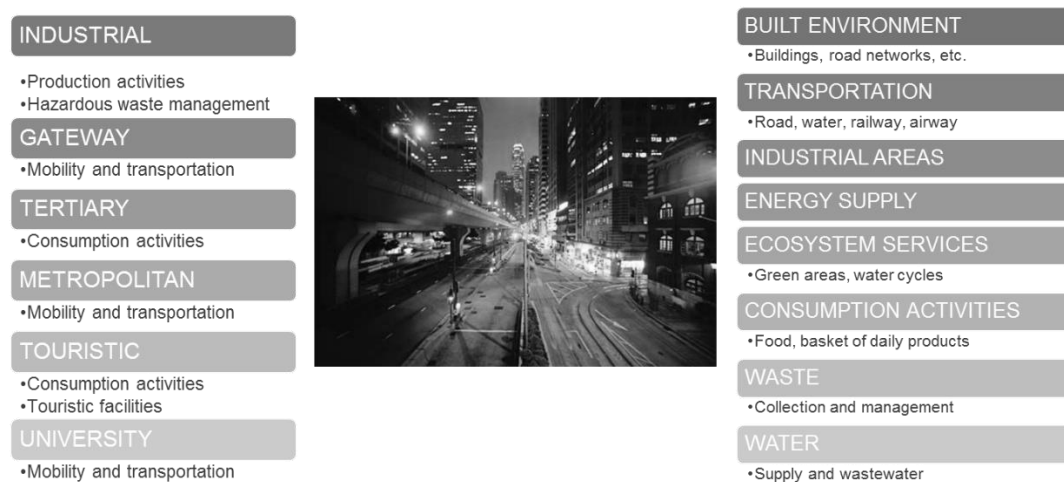
The City EF proposed comprises five main steps, iterative and customizable according to the needs and the specific reality of the urban context taken into account (Figure 3).



**FIGURE 3** City Environmental Footprint, methodological details of the proposed approach

The first step entails a qualitative approach and aims at providing an overview of the dynamics inherent to the city, with the study of the historical, social, and economic background, through the identification of the main functions and the support of specific urban indicators (Figure 4). A core set of horizontal indicators is dedicated to describe the dynamics common to each urban context, while specific sets are dedicated to each urban categories identified.

Furthermore, proper definitions and methodological guidelines for various urban contexts complete the qualitative step of the City EF. The final aim is to provide the necessary elements to support the following quantitative approach. Indeed, as a unique definition of “city” does not exist yet, a careful reflection on this issue is not crucial only from a semantic point of view, but also from a technical one, as it involves the definition of system boundaries for the object investigated.



**FIGURE 4** Categories for cities and their subsystems as proposed in the City EF

The subsequent quantitative approach (LCA based) takes into account the findings emerged from the previous step with specific refinements related to: functions of the system and functional unit, system boundaries, allocation procedures for production/consumption and transportation activities. The definition of the system boundaries shall be carefully done, and even if geographical and administrative boundaries are the most feasible choices, as they are objective, legal, political ways to define the urban context and they support better the data gathering process, it is essential to consider appropriate allocation procedures for the existing transboundary processes (e.g. mobility and trades). Moreover, an adequate functional unit shall describe and account the heterogeneous urban space. Even if referring the yearly flows to a single citizen or to the overall urban population are popular choices, the reference to the “population equivalent” could be a more promising and advantageous concept, able to consider not only the permanent residents, but also the city-users, share of people taking advantage of the urban services (e.g. tourists, commuters, etc.).

The life cycle inventory follows (step three), and it is organized according to the different urban subsystems identified in the qualitative step. Data about each subsystem are collected and organized in coherence with the identified function of the city and functional unit (entire urban system and number of population equivalent identified). A feasible level of data quality and granularity, that could maximize the efforts and provide robust and consistent results in a reasonable time, shall be defined. Learning from the previous analysis, an innovative way could be the combination of common “low-tech” data (statistics, literature, etc.), with “high-tech” data, e.g. spatial data from GIS.

The fourth step translates the inventoried fluxes in potential environmental impacts. In this regards, appropriate models and LCIA methods are used, but they shall be carefully considered to address better the spatialization of impacts and the identification of global (e.g.

climate change), regional (e.g. acid rain) and local (e.g. air quality) impacts for a more effective and conscious decision-making process.

Finally, the fifth and conclusive step is dedicated to revisions, interpretation of results, investigations on the major hotspots. Sensitivity analysis and evaluation of alternative improvement scenarios are possible additional steps.

#### **4. CONCLUSIONS AND FUTURE OUTLOOK**

Cities are a strategic player in the path towards sustainability, but their complexities require an ad-hoc methodology to achieve the target, as no methodology to date is completely effective. This contribution shows that so far none of the available approaches and selected methods can be applied as it is, but each one provides good points to start or working points to start. The proposed City Environmental Footprint aims at overcoming some of the macroscopic current limitations, such as: i) the assessment of potential impacts induced by urban activities; ii) the identification of the major hotspots and responsible actors; iii) the evaluation of more sustainable alternative scenarios to select the best measures from an environmental point of view. Currently, investigations are ongoing to define and test proper system boundaries, functions and functional unit of the system, and provide methodological advancements for a more specific urban impact assessment. Future advancements could be the extension of the methodology for the evaluation of social and economic dimensions through the support of Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC).

Finally, the intended final users of such method are urban planners, policy makers, researchers and practitioners. The City EF aims to be an efficacious tool that can support them in the transition for cities to a more sustainable path.

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## 8. HUMAN WASTE MANAGEMENT, STORAGE AND DISPOSAL IN NIGERIA: IMPLICATIONS TO RESIDENTIAL APARTMENTS IN IKEJA, LAGOS

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**ABSTRACT.** Human waste is as important to mankind as life itself. As people feed for survival, the process of digestion leads to the production of human waste. Lagos being a Mega city with a population of more than fifteen million, the human waste generated is significant. How the generated human waste is handled is worthy of assessment. This paper examines the methods through which human wastes are collected and disposed in Ikeja residential quarters. The case study has the three classified residential zones of high density, medium density and low density. Sample frame was based on the number of buildings. Findings reveal that, residents across the density zones rely basically on septic tanks for human waste storage, which leads to a recommendation that septic tanks and soakaways be kept at appropriate distances to boreholes and wells, to prevent water contamination.

**Keywords:** Human waste, Storage and Disposal, Residential Apartment.

### 1. INTRODUCTION

How human waste is kept and processed will determine its resultant effects on the environment and the lives of citizens. In Ikeja, the capital of Lagos State, Nigeria, human wastes are generally subjected to onsite storage, just like most areas of Lagos State. This is done through the construction of septic tanks and soakaways. The absence of sewer system in this area makes it mandatory for each house to owner to store human wastes within the limits of their sites. This practice has become traditional, and usually carried out without putting the World Health Organisation recommended safe distance of 30 metres into consideration<sup>3</sup>

Population growth and change in lifestyle coupled with industrial growth are major causes of waste increase in developing nations<sup>1</sup> (Majeswari et al, 2017)

Human faeces and urine, which are products of living beings are a huge contributor to wastes in the world. Human faeces contain organisms that are capable of causing diseases, by getting into the body through food, water or any contaminated object. These often leads to diseases like diarrhoea, cholera or typhoid that could result to death, if not promptly and properly treated<sup>2</sup>. However, the dangers caused by these human waste makes it imperative that it be properly managed, in order to achieve sustainable living.

Several issues have been found to be connected with human waste mismanagement in Lagos State, Nigeria, these include; air pollution that results from the overflow of un-evacuated septic tanks, contaminated underground water and accidents due to badly constructed septic

tanks and soakaways (Figures 3 & 4). It is then valuable to study the management pattern of human wastes in Ikeja, Lagos State.

Two main identified problems guide the focus of this write-up. The first is the absence of sewer lines in the study area and the resultant proliferation of septic tanks. The second is the absence of an effective community water supply, which also leads to home owners having to either drill bore-holes or dig wells. The study seeks to access Septic Tank/Soak-away placement vis-à-vis bore-holes and septic tanks, and also explore solutions to the resultant challenge of these placements. The results from this study will point to steps that could make neighbourhoods and buildings more sustainable.

## **2. REVIEW**

### **2.1 Human Waste and Underground Water**

It is generally accepted that human waste is a major contributor to environmental pollution in developing countries. About 98% have access to toilets and onsite technologies are usually deployed through septic tanks and soakaways to manage the wastes generated through the use of the toilets<sup>5</sup>. These technologies are considered safe when handled to specifications<sup>6</sup>. More than 80% of Nigerians depend on this system for sanitary wastes<sup>3</sup>.

However, the peculiar situation of developing nations, like corruption, absence of maintenance and population increase, usually causes inadequate water distribution through government controlled infrastructure. This situation has forced individual property owners to find alternative source of water supply, hence, the proliferation of boreholes and wells<sup>7</sup>. In Nigeria, people depend mainly on the for drinking and other uses<sup>3</sup>.

For the contamination of this ground water, a major source is believed to be the septic tank system. This is because septic tanks and soakaway pits are located with disregard to the World Health Organisation (WHO) recommended distance of 30m – 40m. This is in addition to boreholes being done without taking the UNICEF recommended minimum depth of 100m – 150m into consideration<sup>3,8</sup>.

### **2.2 Brief description of standard septic tank/soakaway in Nigeria**

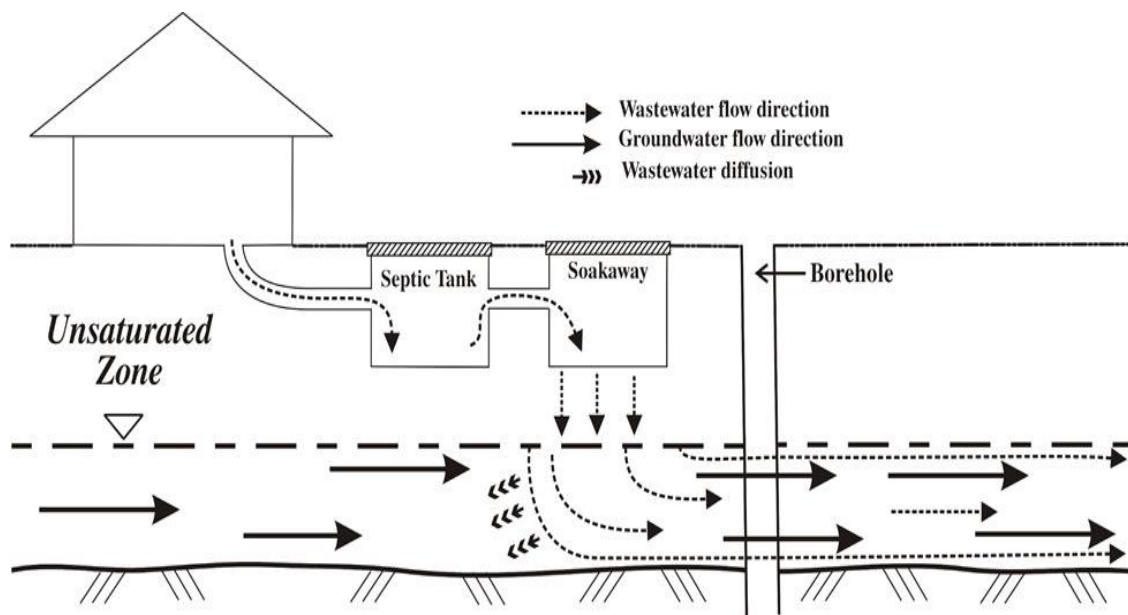
Septic tank is a sealed, watertight concrete tank used for onsite sewage treatment. It uses the anaerobic bacteria environment to reduce solid wastes and organics. The tank is divided into 2 chambers provided with individual manhole cover. It is separated by a baffle wall with opening close to the roof and floor of the tank. The inlet of the solid waste goes straight to the sedimentation section where the waste gets decomposed and mineralized leaving the sludge to settle at the base, the scum to float and the waste water at the middle. The wastewater flows to the second chamber for further settlement leaving behind an almost clear wastewater, which is transported to the soak away for primary treatment. Septic tanks vary in sizes based on the number of users within the facility. It is provided with vents and access points for inspection.

The soak away pit is another underground structure away from the septic tank. It is a drywell commonly used to drain out the waste water from the septic tank. It allows soil water to slowly

percolate into the ground. In Nigeria, these soak-away pits are often made of sandcrete block walls laid along the excavated pit walls with gaps to allow the water to seep through them to the ground. However, this is meant to allow the water go through the earth to naturally filter out but it may cause ground water pollution causing the water sources around to be contaminated.

These two (septic tank and soak away pit) covers a large portion of the building setback and is normally covered with concrete slabs and well supported to avert the possibilities of failure when heavy objects pass across it.

### 2.3 Implications of siting Septic tanks/Soakaways close to Boreholes



**FIGURE 6:** Representation of the effects of Septic tank and Soakaway pit on ground water<sup>3</sup>.

## 3. STUDY AREA

The case study approach was adopted for the study. The specific case selected was Ikeja. Lagos State, where Ikeja is situated, was created on the 27<sup>th</sup> of May, 1967, through States Creation and Transitional Provision Decree No 14 of 1967. Before this time, Lagos municipality was administered as a Federal Territory by the Federal Government. The State took off fully as an administrative entity on the 11<sup>th</sup> of April, 1968. It is the 6<sup>th</sup> largest city in the world, with the smallest landmass in Africa. It is West Africa's most resourceful single trading market with highest concentration of people. It has an area of 358,861 hectares or 3,577sq.km. Lagos is located on the Atlantic coast in southern Nigeria<sup>9</sup>

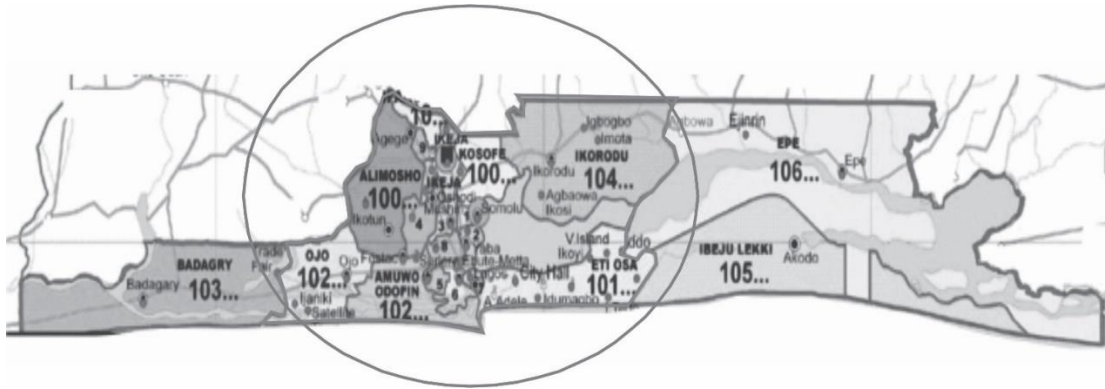
The rate of population growth is about 600,000 per annum with a population density of about 4,193 persons per sq. km. In the built-up areas of Metropolitan Lagos, the average density is over 20,000 persons per square km. Current demographic trend analysis revealed that the State population is growing ten times faster than New York and Los Angeles with grave implication for urban sustainability<sup>10</sup>.

Lagos has a diverse and fast-growing population, resulting from migration to the city from all parts of Nigeria and neighbouring countries. This is the only urban settlement in the UN list of 30 largest urban settings in the world (Cohen 2004). In 1992, Lagos had an estimated population of about 1,347,000. The population of its metropolitan area was about 10.1 million in 2003. The United Nations predicts that, the city's metropolitan area, which had only about 290,000 inhabitants in 1950, will exceed 20 million by 2010, making Lagos one of the world's five largest cities<sup>11</sup>



**FIGURE 7.** Map of Nigerian, showing the location of Lagos<sup>12</sup>





**FIGURE 8.** Map of Lagos State, showing Metropolitan Lagos in red highlight<sup>13</sup>

Ikeja, the study location, is the capital of Lagos State of Nigeria. This city was pronounced the capital in 1976. This area has economic, social and material potentials, it also has its environmental and physical challenges. Ikeja covers 5,630 hectares of land area, which accounts for 1.57% of the state's total area. It however accommodates 3.45% of the population, which is a total of 533, 237. It is projected to become 1,062,833 in 2020. Lagos state house survey 2010, takes the population of Ikeja to be 735, 828. It is documented that, 85% of the buildable space in Ikeja has already been utilized.



**FIGURE 9.** Map of Lagos State, showing sixteen of the existing twenty Local Governments in Metropolitan Lagos; Ikeja Local government in oval circle<sup>14</sup>.

For ease of administration and political monitoring, Ikeja is divided into 10 wards, namely:

1. Anifowose/Ikeja
2. Ojodu/ Agidingbi/Omole
3. Alausa/Olusosun/Oregun
4. Airport/Onipetesi/Onilekere
5. Ipodo/Seriki Aro

6. Adekunle Village/Adeniyi Jones/Ogba
7. Oke-Ira/Aguda
8. Onigbongbo/Military Cantonment
9. GRA
10. Wasimi/Opebi/Allen

Ikeja is also noted for industrial activities apart from having most of its land area dedicated to residential. It carries 46.4% of manufacturing production values, the highest in Nigeria as at 2014.

The population induced pressure on Ikeja has made the existing infrastructure inadequate for the populace, which led to the degeneration in the quality of life and physical environment.

The choice of Ikeja as a study area is due to its being the capital of Lagos State where the presence of the state government is domiciled. It also has a representation of the 3 major income groups; low income/high density/medium income/medium density and high income/low density. Apart from its being predominantly residential, industrial and commercial activities are also located in this study area.

## 4. RESEARCH METHODS

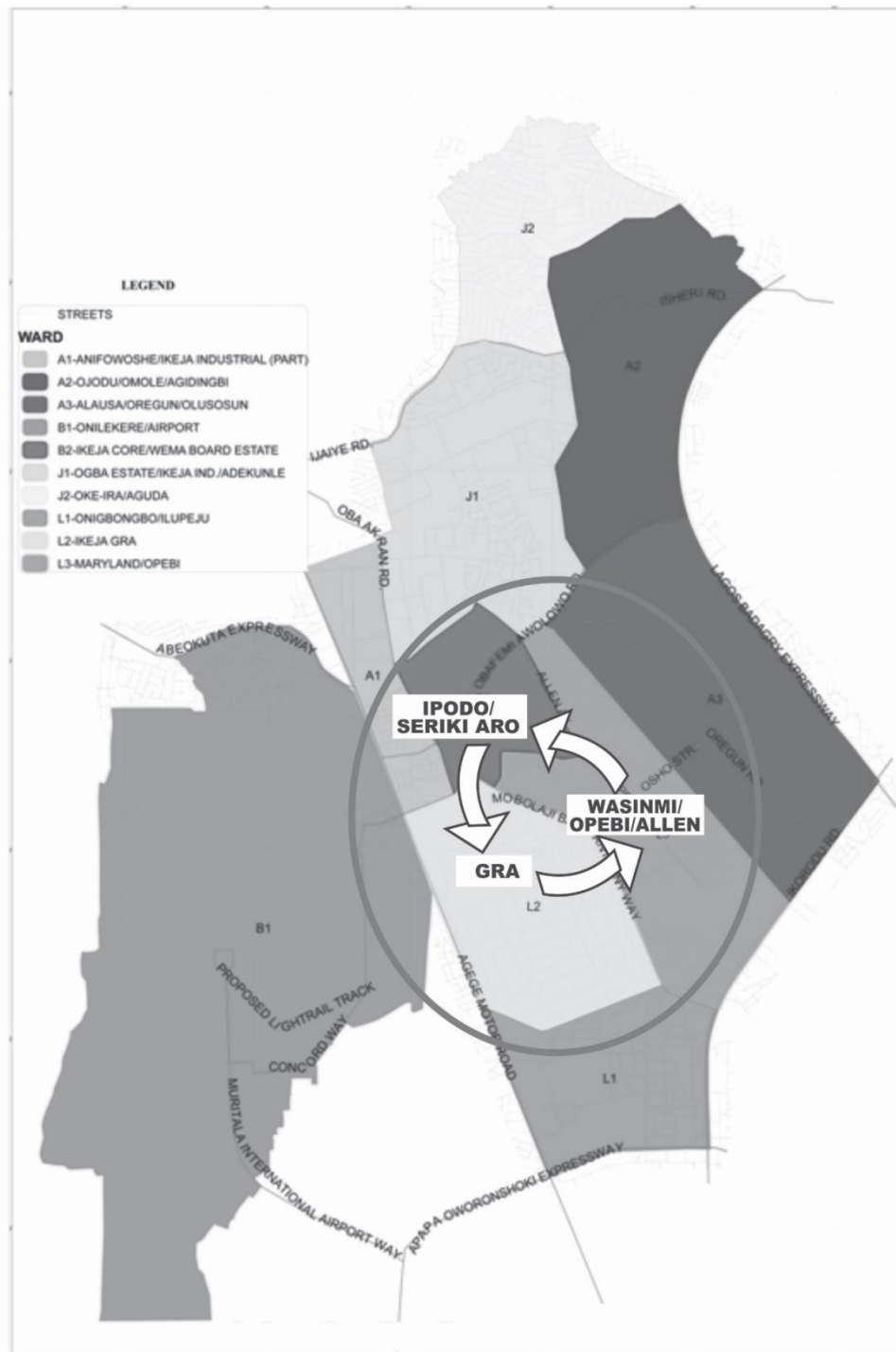
### 4.1 Sampling technique

The study area has all the classified wards in it; low density, medium density and high density income wards (table 2). It was purposively selected, due to its being the capital of Lagos State.

**TABLE 1:** Wards within Ikeja Local Government

<b>HIGH DENSITY/LOW INCOME WARD</b>	<b>MEDIUM DENSITY/MEDIUM DENSITY WARDS</b>	<b>LOW DENSITY/HIGH INCOME WARDS</b>
1. Ipodo/Seriki Aro	Anifowose/Ikeja	Onigbongbo
2.	Agidingbi/Omole/Ojodu	GRA
3.	Alausa/Oregun/Olusosun	
4.	Onilekere/Onipetesi	
5.	Adeniyi Jones/Ogba	
6.	Okeira/Aguda Titun	
7.	Wasinmi/Opebi/Allen	

Ipodo/Seriki Aro, the only high density ward in Ikeja was selected, Wasinmi/Opebi/Allen was randomly selected from the medium density wards, while GRA was equally selected randomly, from the low density wards.



**FIGURE 10:** Randomly selected wards for administration of questionnaires<sup>15</sup>

Questionnaires were administered in selected residential buildings within these wards.

## 4.2 Sampling unit

The total number of residential buildings in Ikeja is 25,313, and number of polling units 350 (Independent National Electoral Commission, 2000). This gives an approximate 72 buildings per polling unit. When applied to these three wards, by working out the number of buildings in each ward through the application of the ratio of polling units per ward, considering that, the

number of polling units was determined, by the number of residential buildings in each of the ward, the figures are as shown in table 3.

This gives a population of 7,953 buildings, as the basis for sampling.

**TABLE 2:** Selected wards. Source: Independent National Electoral Commission (2000)

WARD	AVERAGE No OF BUILDINGS/POLLING UNIT X No OF POLLING UNITS	POPULATION (Residents) BASED ON No OF BUILDINGS
1. Ipodo/Seriki Aro	72 X 55	3,960
2. Wasimi/Opebi/Allen	72 X 30	2,160
3. GRA	72 X 25	1,800
TOTAL	72 X 110	7,920

The sample size of this research was based on the population of residential buildings in selected wards, which is 7,953. Questionnaires were administered on the basis of this estimate.

### 4.3 Sample size

The sample size was determined in reference to table 4, at a confidence level of 95% and a margin error of 5%.

**TABLE 3.** Sample size requirements

Source: <https://edis.ifas.ufl.edu/pdf/EDIS/ED00600.pdf>

Size of Population	Sample Size (n) for Precision (e) of:			
	±3%	±5%	±7%	±10%
500	a	222	145	83
600	a	240	152	86
700	a	255	158	88
800	a	267	163	89
900	a	277	166	90
1,000	a	286	169	91
2,000	714	333	185	95
3,000	811	353	191	97
4,000	870	364	194	98
5,000	909	370	196	98
6,000	938	375	197	98
7,000	959	378	198	99
8,000	976	381	199	99
9,000	989	383	200	99

A total number of 750 questionnaires (about double the size of the recommendation on table 4) were administered in the 3 zones. The total number of returned questionnaires were 595, which accounts for 79.3%. The number of questionnaires analysed were 545 (72.7%), after the ones with errors were separated.

## 5. FINDINGS

On the type of toilet facility used by respondents (Table 5), 93.8% use flush toilets within high density area, 97.2% within the medium density area, 96.6% within the low-density area, while 96.0% of them use flush toilets at the combination of the 3 density areas. There is no existing sewer to carry the wastes generated through these toilet systems. Every building stores the resultant wastes from its toilet facilities onsite. The 25,313 number of buildings in Ikeja, is closely related to the number of Septic tanks and soak pits in existence.

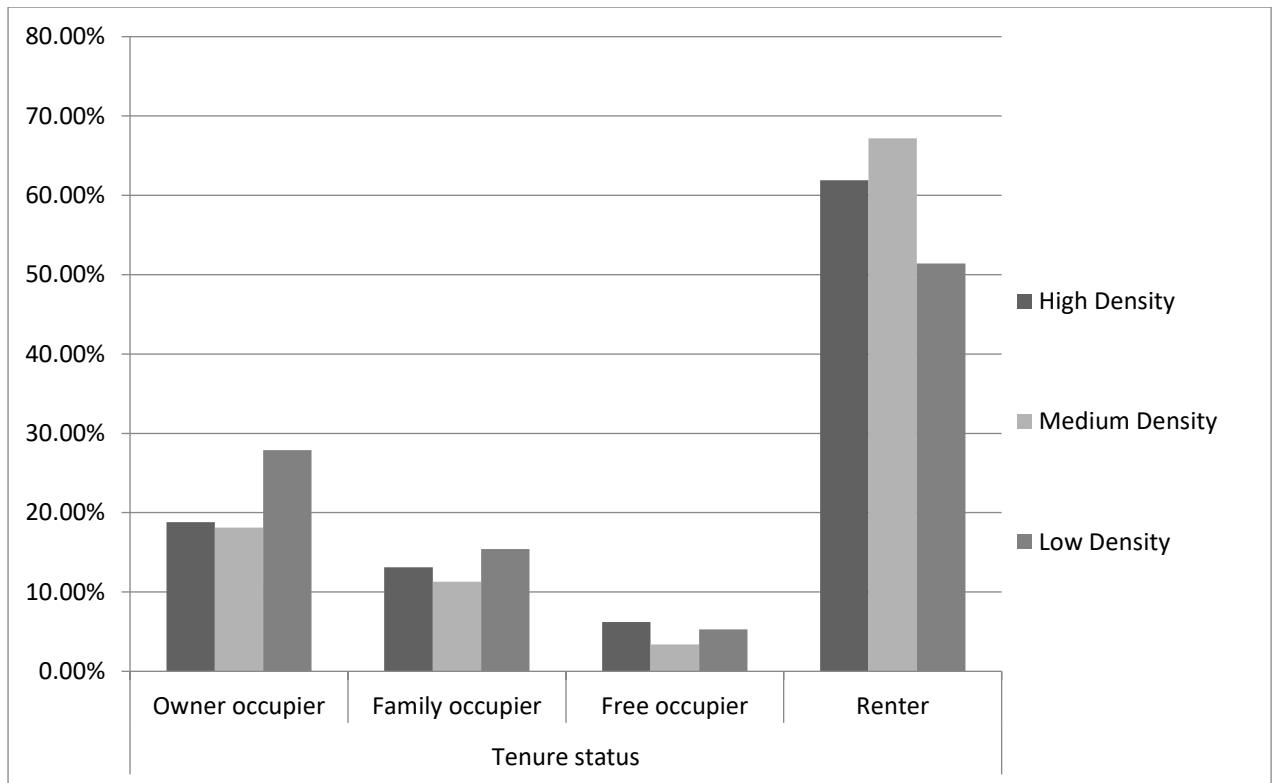
For water supply, majority of respondents rely on private bore-holes or wells (Table 5), this is evident within the 3 density areas and across the generality of respondents. This is 61.2% within the high density area, 70.1% within the medium density area, 70.7% within the low density area and 67.7% at the combination of all density areas.

Most respondents (73.2%) have never been enlightened through programmes on the sustainability of the environment and dwellings.

**TABLE 5:** Frequency distribution of Respondents' type of toilet facility, mode of water supply and sustainability awareness

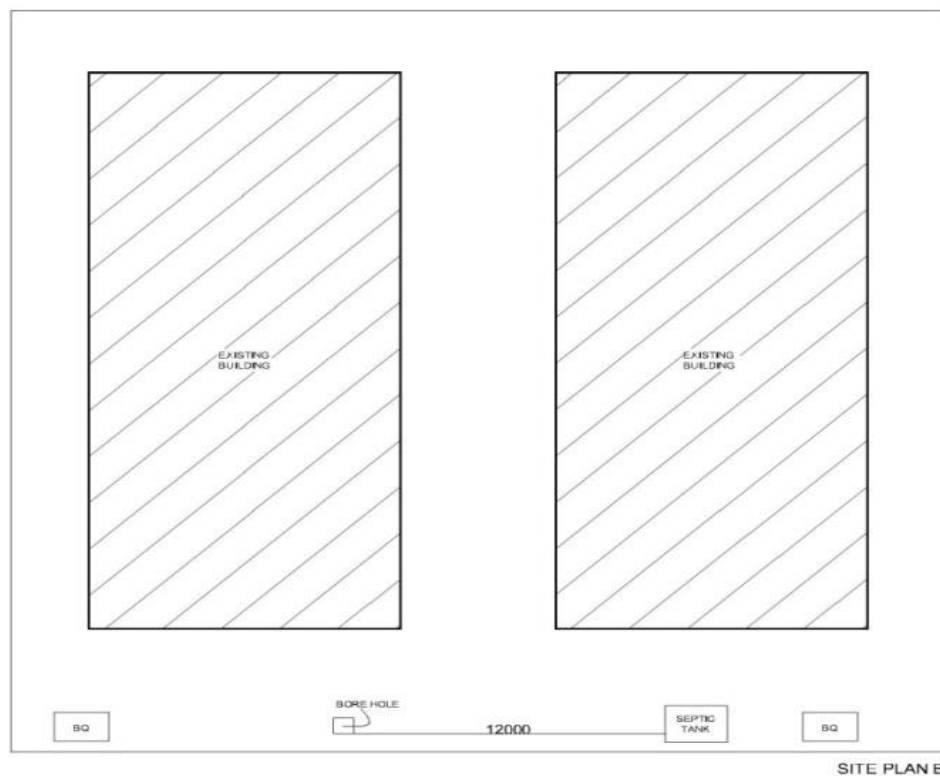
		High Density	Medium Density	Low Density	Total
Water Supply	Pipe-borne water	48(30%)	38(21.5	45(21.6	131(24.0
	Private bore-hole/Well	98(61%)	%)	%)	%)
	Water Vendors, Rain Water	13(3.1%)	124(70.1	147(70.7	369(67.7
	)	%)	%)	%)	%)
		1(0.6%)	14(7.9%)	12(5.8%)	39(7.2%)
		)	)	)	)
			1(0.6%)	4(1.9%)	6(1.1%)
Toilet Facility	Flush Toilet	150(93.8	172(97.2	201(96.6	523(96.0
	Pit Latrine	%)	%)	%)	%)
		10(6.2%)	5(2.8%)	7(3.4%)	22(4.0%)
		)			)
Involvement in sustainability Programme	Yes	45(28.1	51(28.8	50(24.0	146(26.8
	No	%)	%)	%)	%)
		115(71.9	126(71.2	158(76.0	399(74.2
		%)	%)	%)	%)

However, majority of respondents within each income zone are Renters; 61.9% in the low income zone, 67.2% in the middle income zone, 51.4% in the high income zone and 59.5% in all combined. This is followed by owner occupiers, with 18.8% within the low income zone, 18.1% within the middle income, 27.9% within the high income and 22.0% within all respondents combined. This has a significance difference of 0.059.

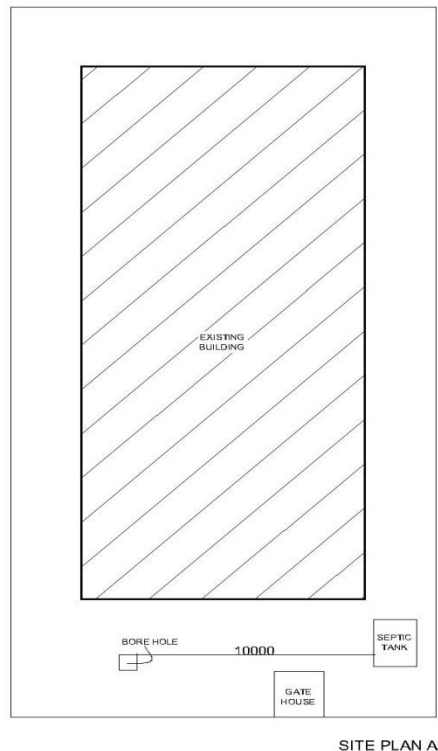


**FIGURE 11:** Tenure status of respondents across density zones

Physical assessment of the study area, shows the borehole distance to septic tanks and soakaway pits to be 12 metres and below. This is grossly inadequate as it does not conform with World Health Organisation (WHO) recommendation.



**FIGURE 12:** Borehole distance to Septic tank and Soakaway pit in a selected compound



**FIGURE 13:** Borehole distance to Septic tank and Soakaway pit in a selected compound

## 6. RECOMMENDATIONS

Residents are at the risk of being infected by diseases related to water and sanitation endemic in sub-Saharan Africa, especially through oral infection. These include Cholera and Typhoid<sup>16</sup>. There is a higher risk of infection when there are no well-designed housing strategies and the creation of healthy environments by stakeholders<sup>17</sup>. It is therefore recommended that:

1. Awareness is created for stakeholders to know the health hazards and environmental nuisance that could arise due to mismanagement of Human waste.

The location of septic tanks to buildings should be a minimum of 30 metres<sup>3</sup>. An average plot of land in Ikeja, Lagos cannot accommodate such distance to the building. This makes centralised storage an option. It is therefore recommended that:

2. Neighbourhood based treatment plants should be established with a network of sewer lines

A greater percentage of respondents are renters (Figure 11), who have no control on the properties as built. Based on this, it is recommended that:

3. Regulations that will compel the investors to imbibe sustainable practice be put in place.

The following are also recommended:

4. Establishment of pressure groups that will compel government agencies to formulate policies on human waste management.
5. There is a need for researchers, to focus on developing nations especially in the area of Waste management

## 7. CONCLUSION

Viewing the composition of Lagos State, and the entire country, centralised human waste management is not a common experience. Establishment of centralised Human waste treatment plants, and a massive education of residents on the risks associated with unsustainable practices will gradually lead the neighbourhoods towards resilience. Findings and Recommendations from this research serves as a lead towards further studies on this subject.

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## APPENDIXES



**FIGURE 14.** A typical soakaway construction in Lagos



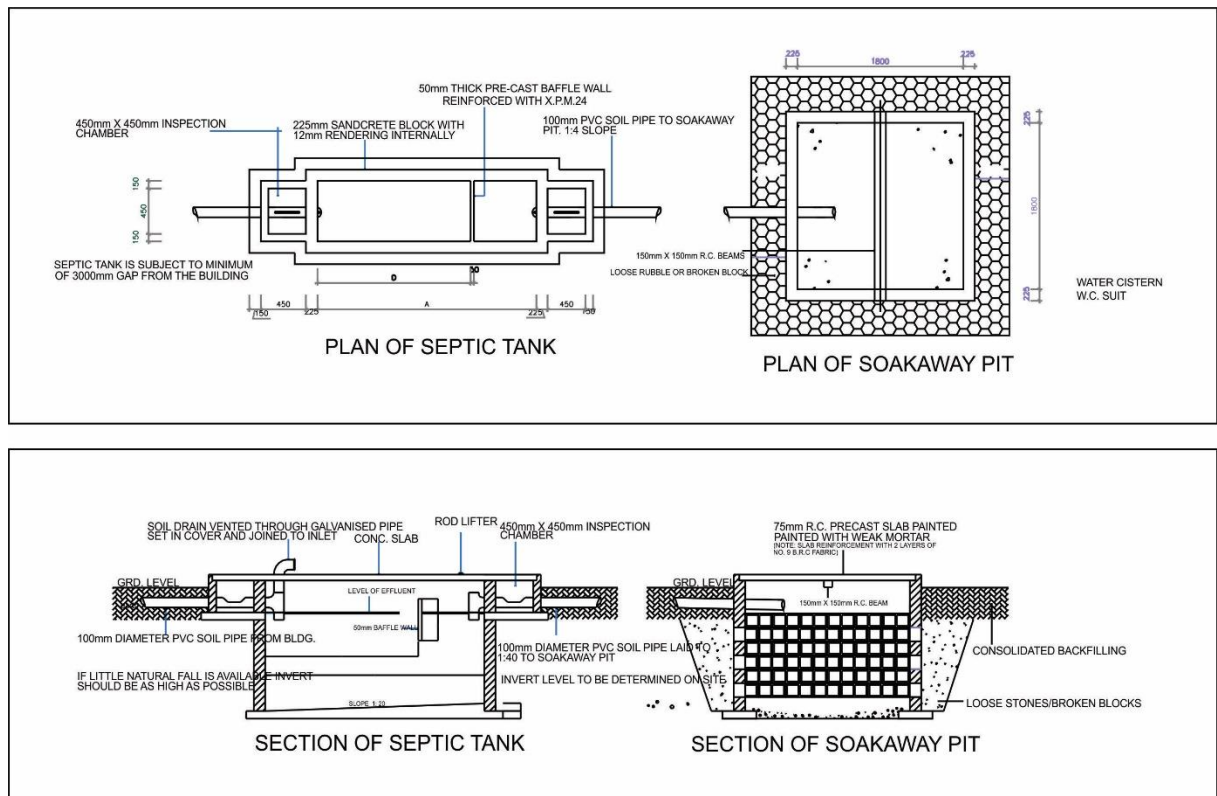
**FIGURE 15.** A typical Septic tank construction in Lagos



**FIGURE 16:** An exposed Septic tank with rubbles, within the Lagos Metropolis. Source<sup>4</sup>



**FIGURE 17:** A damaged Septic tank that has become a danger to residents, within the Lagos Metropolis. Source<sup>4</sup>



**FIGURE 18:** Plans and sections of a typical Septic tank and Soakaway pit in Nigeria

## 9. DEVELOPMENT OF SOCIAL CAPITAL MANAGEMENT APPROACH WITH RESIDENT PARTICIPATION USING IMPROVED RESOURCE GENERATOR METHOD

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**ABSTRACT.** In this research, based on the idea that it is important for urban sustainability and resilience to pass on healthy underlying stocks to the next generation, we developed a bottom-up method for managing social capital and applied it to Yachiyo City, Chiba Prefecture, Japan. The developed method is as follows. First, we conducted group interviews among residents to extract important social relationships for the region. Using the results, we created a resource list for the resource generator and grasped the present state of social capital using this list. Finally, we implemented workshops for residents to revitalise social capital. The results are as follows. First, group interviews revealed that expressive resources are important in addition to instrumental resources. Second, the resource generator survey extracted weak points of social capital in Yachiyo City. Third, at the workshops, several specific ideas were proposed by citizens. From the above, the effectiveness of our method was confirmed.

**Keywords:** Social capital, Stock management, Resource generator, Resident participation, Workshop

### 1. INTRODUCTION

It is extremely important to appropriately maintain and manage various underlying stocks at the community level and hand them over to future generations for a sustainable society [1]. Underlying stocks are human capital, manufactured capital, natural capital, and social capital [2]. It has been pointed out that these stocks can reduce vulnerability and increase community resilience [3]. Therefore, grasping and managing these stocks leads to the sustainability and resilience of cities.

Especially, we are paying attention to social capital among various stocks. In recent years, a wide variety of disciplines and decision-makers have become more interested in such. According to Putnam (2000), social capital is defined as 'social networks and the norms of reciprocity and trustworthiness that arise from them' [4]. Social capital has attracted increased attention because it is expected to improve efficiency in society, have a positive effect on the decrease in regional unemployment rates, and enhance the health and safety of residents. Moreover, it is pointed out that social capital is useful at the time of disasters and recovery, and for social relational approach to natural resource governance [5, 6]. In other words, the effects generated by 'norms of social network and interdependence' are expected in many fields. These effects should lead to regional sustainability and resilience as well as an increase in people's happiness level.

Nonetheless, there are some challenges to conceptualization and operationalization of social capital [7]. The first challenge is defining social capital. Definitions of social capital and its expected utility are various, and when such definitions are not explicit, it is unclear what to manage. The second challenge is quantitative and qualitative understanding of social capital. There is great variability among measurement methods, effects expected, and scales applied by researchers in previous studies. In other words, we should develop a bottom-up approach to measure social capital for management purposes. The third challenge is how to plan for management of social capital in actual circumstances. Building and maintaining of networks for cooperative relationship or reciprocity depends on the practice of residents in particular communities. To some extent, human capital, manufactured capital and natural capital can estimate the future state using statistical data with a forecasting approach. But, without resident participation on research, it is difficult to grasp the present and future state of social capital.

Based on the above, the purpose of this study is to develop an approach to measure and manage social capital. If this purpose is achieved, it will be possible to identify vulnerabilities and strengths of social capital, and to reduce its vulnerabilities and utilize its strengths in actual communities.

## **2. METHODOLOGY**

### **2.1 Resource generator**

First, in this study, we defined social capital as ‘the social relations (networks) and their benefits’. Next, we reviewed various methods to measure social capital, ultimately adopting the resource generator method. In this methodology, interviewees were asked about the existence of acquaintances from whom they could obtain cooperation; descriptions of the relationships were also explored [8–10]. We presented 30 items (resources) that require cooperation from others. For example, we asked, ‘Do you have any acquaintances whom you can ask to take care of your parents or children?’ If a person answered yes, then the person was judged as having access to a resource. However, we thought previous studies using this methodology has a problem. In previous research, researchers created a list of resource items (hereinafter, a ‘resource list’), but these resources may not be important for residents.

### **2.2 Social capital management**

We considered performing a following procedure. First, we conducted group interviews with residents about resources from social relations required in the future. Next, based on the results, we created a resource list for the resource generator. This method can create a list of resources more important to residents than to create them by researchers only. Moreover, we disseminated a survey questionnaire with the resource list to grasp the current state of social capital. Finally, we held citizens’ workshop regarding ways to create networks among people with little social capital with this survey results. This method can be expected to reduce the vulnerability of social capital.

We applied this approach to measure and manage social capital in Yachiyo City, Chiba Prefecture, Japan. This city is a dormitory suburb of the Tokyo metropolitan area, located about 30 km from Tokyo station.

**TABLE 1.** Instrumental and expressive resources

Type	Instrumental resource	Expressive resource
For example	physical and financial support, information and product provision, introduction of people and work	mental support, empathy, acceptance, companionship, encouragement for personal growth

### 3. RESULTS

#### 3.1 Group interviews

We conducted group interviews on August 2015 with 20 participants (residents) selected from a larger number of applicants. Those selected were placed into four groups of five people who were diverse in terms of generation and gender. The discussion theme was ‘What resources (social relationships) do you think you will need in the future?’ Because it is difficult to estimate the social capital with the forecasting approach, we adopted a backcasting approach regarding social relations that participants considered necessary (retrospectively) for setting future goals and conducting management. We identified 162 resources from these group interviews and divided them into ‘instrumental’ and ‘expressive’ resources (Table 1) [11, 12].

Instrumental resources, adopted mainly in previous research studies, included the provision of information and products, the introduction of people and work, and physical and financial support. Examples from the interviews are as follows: ‘ask to take care (temporarily) of own parents or children’, ‘ask someone to drive to destination (hospital, station, etc.)’, and ‘ask someone to offer support when one is sick or has a disability’. Meanwhile, in the groups interviewed, participants suggested many expressive (emotional) resources, such as mental support, acceptance from others, and stimulation for personal growth. Examples include ‘to listen to one’s problems and complaints’, ‘to give motivation and enthusiasm’, and ‘to be accepted’. Technology, services, and goods can replace instrumental resources. However, it is difficult to obtain expressive resources from outside one’s social network. In other words, expressive resources will be important in the future in Japan.

#### 3.2 Resource list

We created a resource list of 30 items based on the results of group interviews (Table 2). Of these items, 13 are common with our previous studies [8]. Many of the newly added ones are expressive resources.

**TABLE 2a.** Resource list based on group interview (NO.1-10)

NO	Resources
1	... can show you nice restaurants
2	... you can rely on when problems occur with your PC and smartphones
3	... you can you can exchange hobby information
4	... you can ask to do shopping when you are sick
5	... can drive you to your destination when you can’t drive yourself (e.g. when you don’t have a license)
6	... you each know of the other’s family composition

7	... you can tell each other's present situation
8	... you can share information about evacuation area in times of disaster and safety confirmation method
9	... you can make a simple request such as watering when you go away for a long time (travel etc.)
10	... you can ask for sending supplies required at the time of disaster

**TABLE 2b.** Resource list based on group interview (NO. 11-30)

NO	Resources
11	... do a local activities (local festivals, volunteers, etc.) with you
12	... you can enjoy hobbies with and exercise together
13	... always care about you and your family
14	... you can talk to about local history, environments and nature
15	... have values and experience different from your own
16	... you can share items (vegetables, souvenirs, etc.) each other
17	... gives you items that are no longer used (children's clothes, electrical appliances, etc.)
18	... can lend you small amounts of money in times of need
19	... you can ask to be your guarantor
20	... can mediate regarding you and your family's place of work (including part-time)
21	... you can go out for eating/drinks together
22	... listens to your problems and complaints
23	... you can ask to take care (temporarily) of your parents or children
24	... can provide you with information in relation to hospitals, care facilities, support systems
25	... you can ask for physical support (care etc.)when you are sick or have a disability
26	... can translate or interpret English
27	... can give you advice on financial matters (insurance, investment and loans etc.)
28	... accepts you just as you are
29	... you can easily ask anything
30	... you can improve through friendly competition

### 3.3 Survey questionnaire using the resource generator

We conducted a survey in January 2016 with this resource list to grasp the status of social capital. We mailed a questionnaire to 3,003 people who were extracted by stratified random sampling, and 907 responses were sent back for a response rate of 30.2% (Table 3).

**TABLE 3.** Profiles of respondents

Attribute		Respondents	%
Gender	Males	396	43.7
	Females	499	55.0
Generation	20's	104	11.5
	30's	125	13.8
	40's	167	18.4
	50's	129	14.2
	60's	174	19.2
	70's and over	198	21.8
Housing	Detached	593	65.4

Household	Flat (ownership)	130	14.3
	Flat (rental)	164	18.1
	Single	57	6.3
	Two	304	33.5
	Three and over	494	54.5

**TABLE 4.** Accessibility rate of each resources (acquisition source)

NO.	Total	The acquaintance's place of residence				
		living together	neighborhood	local community	in the city	out of the city
1	90.8	62.3	43.8	40.2	43.4	58.3
2	85.1	58.9	16.0	16.9	20.8	46.0
3	86.1	41.7	29.0	30.3	34.1	58.0
4	89.3	78.1	24.5	15.2	14.6	19.7
5	91.6	60.1	54.7	39.4	38.8	62.7
6	86.3	66.6	26.6	20.3	20.2	27.9
7	91.4	59.1	34.1	30.2	32.4	64.9
8	81.3	67.9	25.1	13.6	10.8	18.5
9	73.2	52.5	35.4	10.3	8.7	11.6
10	83.5	31.8	17.0	16.0	19.1	67.5
11	55.7	31.1	29.1	20.7	11.2	7.3
12	78.7	43.1	23.4	23.0	25.6	39.5
13	89.2	57.4	31.4	21.6	21.7	51.8
14	69.6	48.5	29.3	21.3	16.9	18.4
15	78.9	37.5	21.8	22.4	27.7	54.7
16	84.8	31.4	55.7	30.0	26.7	39.4
17	55.0	16.3	19.3	17.1	16.0	32.9
18	63.3	42.1	8.4	7.4	10.9	35.0
19	65.7	39.7	6.6	5.7	9.9	37.4
20	41.3	16.9	7.5	8.4	9.5	26.0
21	51.5	31.4	6.2	6.6	8.8	29.2
22	89.4	63.2	26.7	27.1	31.5	61.4
23	76.7	50.7	19.1	11.8	13.9	32.7



24	80.5	39.1	38.0	30.8	31.5	33.4
25	79.3	65.2	11.1	8.3	11.0	28.3
26	35.6	13.6	3.7	3.3	4.4	20.0
27	66.8	29.7	16.8	15.9	18.0	37.7
28	63.0	28.1	11.2	12.1	16.8	39.5
29	91.0	59.5	27.3	31.6	39.7	65.2
30	87.8	65.0	18.7	21.2	26.7	55.2

Table 4 shows the results regarding the accessibility of each resource. The accessibility rate of each resource was generally high. The resources having less than 70% accessibility were numbers 11, 14, 17, 18, 19, 20, 21, 26, 27, and 28. These resources are money-related or highly specialised resources. Moreover, many resources are acquired from families living together.

The analysis of gender and generation showed that females had a greater accessibility rate to each resources than males (Table 5). One reason for this situation is that women are typically more engaged in social relations within a region than men because of child rearing. However, findings of this survey revealed that the average number of acquaintances was larger for men than for women. Many men are acquainted with business contacts, but they indicated that it is

**TABLE 5.** Accessibility rate of each resources (gender and generation)

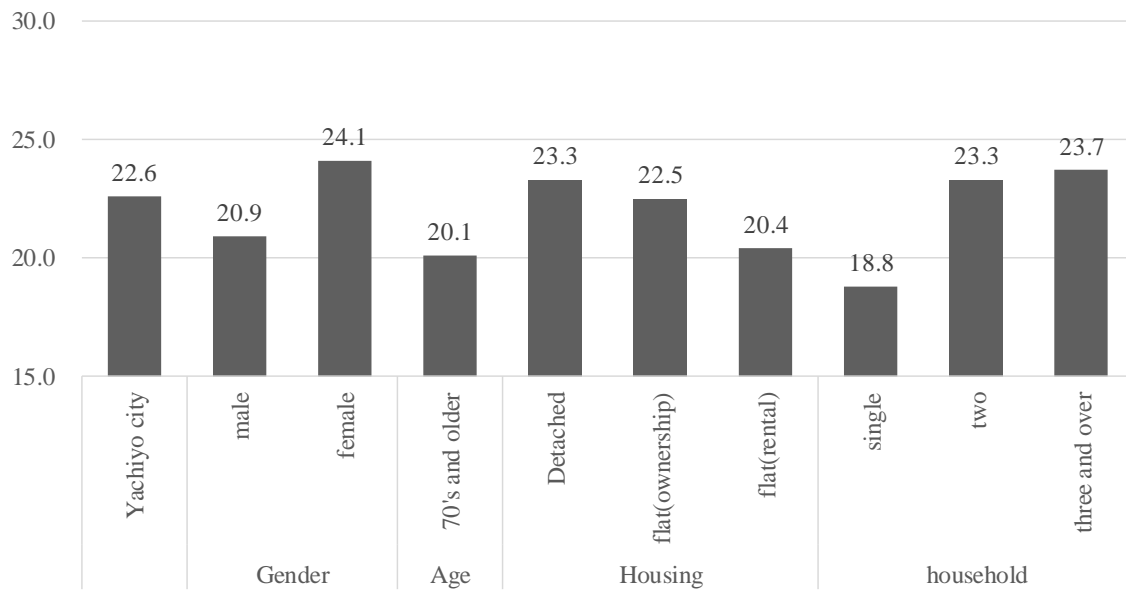
NO.	Males						Females					
	20's	30's	40's	50's	60's	70's	20's	30's	40's	50's	60's	70's
1	90.0	84.1	93.7	84.4	88.1	78.8	95.3	<b>98.8</b>	95.5	95.2	94.4	89.1
2	85.0	77.3	92.4	77.8	81.0	66.3	<b>96.9</b>	<b>96.3</b>	<b>93.2</b>	91.7	91.1	72.8
3	95.0	86.4	84.8	73.3	81.0	75.0	<b>95.3</b>	<b>97.5</b>	89.8	92.9	87.8	78.3
4	87.5	90.9	89.9	84.4	85.7	76.9	89.1	95.1	<b>95.5</b>	95.2	91.1	90.2
5	87.5	90.9	92.4	88.9	88.1	80.8	96.9	96.3	96.6	<b>97.6</b>	94.4	92.4
6	85.0	86.4	89.9	75.6	82.1	67.3	<b>95.3</b>	92.6	92.0	<b>94.0</b>	91.1	85.9
7	90.0	90.9	94.9	91.1	84.5	77.9	<b>100.0</b>	96.3	95.5	<b>97.6</b>	94.4	87.0
8	67.5	88.6	81.0	71.1	82.1	72.1	84.4	85.2	85.2	86.9	83.3	81.5
9	65.0	61.4	63.3	62.2	70.2	71.2	70.3	76.5	79.5	<b>83.3</b>	<b>83.3</b>	72.8
10	75.0	81.8	84.8	84.4	77.4	74.0	84.4	88.9	<b>93.2</b>	<b>92.9</b>	87.8	77.2
11	42.5	45.5	54.4	42.2	53.6	56.7	59.4	58.0	64.8	63.1	54.4	57.6

12	85.0	75.0	75.9	68.9	70.2	71.2	<b>92.2</b>	86.4	79.5	83.3	82.2	77.2
13	62.5	86.4	83.5	86.7	85.7	84.6	92.2	93.8	<b>96.6</b>	94.0	<b>95.6</b>	93.5
14	47.5	65.9	59.5	68.9	70.2	72.1	59.4	67.9	76.1	78.6	<b>80.0</b>	71.7
15	77.5	81.8	82.3	71.1	65.5	62.5	<b>89.1</b>	<b>87.7</b>	<b>90.9</b>	<b>88.1</b>	83.3	71.7
16	60.0	79.5	82.3	73.3	73.8	79.8	79.7	<b>96.3</b>	<b>93.2</b>	<b>95.2</b>	<b>93.3</b>	89.1
17	55.0	61.4	62.0	35.6	42.9	38.5	57.8	<b>82.7</b>	<b>76.1</b>	<b>66.7</b>	46.7	40.2
18	72.5	63.6	65.8	60.0	57.1	38.5	<b>82.8</b>	<b>76.5</b>	71.6	70.2	65.6	51.1
19	60.0	63.6	69.6	62.2	60.7	47.1	70.3	<b>76.5</b>	69.3	<b>77.4</b>	67.8	65.2
20	50.0	29.5	43.0	44.4	33.3	31.7	<b>57.8</b>	50.6	46.6	<b>59.5</b>	34.4	23.9
21	57.5	47.7	58.2	44.4	41.7	28.8	<b>75.0</b>	<b>67.9</b>	58.0	<b>64.3</b>	52.2	35.9
22	90.0	81.8	93.7	86.7	77.4	75.0	<b>96.9</b>	<b>98.8</b>	<b>97.7</b>	95.2	<b>96.7</b>	83.7
23	52.5	70.5	73.4	71.1	73.8	73.1	67.2	<b>88.9</b>	<b>86.4</b>	<b>89.3</b>	80.0	72.8
24	67.5	70.5	82.3	77.8	75.0	73.1	73.4	<b>88.9</b>	<b>92.0</b>	<b>90.5</b>	86.7	76.1
25	75.0	77.3	78.5	73.3	72.6	68.3	79.7	86.4	86.4	<b>88.1</b>	82.2	79.3
26	32.5	36.4	32.9	37.8	27.4	23.1	<b>48.4</b>	45.7	42.0	42.9	32.2	34.8
27	67.5	65.9	67.1	66.7	42.9	46.2	<b>87.5</b>	<b>81.5</b>	<b>77.3</b>	<b>82.1</b>	68.9	59.8
28	62.5	61.4	63.3	51.1	53.6	48.1	<b>82.8</b>	<b>77.8</b>	<b>75.0</b>	71.4	61.1	50.0
29	92.5	88.6	94.9	82.2	85.7	76.9	<b>100.0</b>	<b>98.8</b>	<b>96.6</b>	<b>97.6</b>	92.2	85.9
30	82.5	86.4	88.6	82.2	75.0	75.0	<b>96.9</b>	<b>96.3</b>	<b>96.6</b>	<b>96.4</b>	92.2	83.7

Result of Chi-squared test; Significant **high** and *low* at < 5%

difficult to receive private assistance from such acquaintances. Elderly people aged 70 years or above had the lowest accessibility rate to a significant degree because support from families living together decreases with the independence of children and death of a spouse; association with acquaintances who live far away also decreases for health reasons.

Figure 1 shows the average number of accessible resources, for which there were also gender and generational differences. We analysed the average number of accessible resources in terms of number of people per household and found that single-person households had an average number of 18.8 accessible resources, which was significantly lower than the 23.3 figure for two-person households and 23.7 for households with three or more people. This finding corresponds to the fact that many resources are acquired from families living together. In other words, if an individual becomes a single-person household for some reason, his/her social capital may suddenly become vulnerable even if he/she could access many resources before then. Moreover, in Yachiyo City, there are many people living in rental flats with a



significantly lower average number of accessible resources compared with people living in detached houses.

First, the average household size of a rental flat is smaller than that of a detached house. Generally, in rental flats, the connection between residents is thin, according to a previous study, which may have influenced this result.

These results showed the current situation against the goal set for 2040 regarding resource lists. That is, it demonstrated that 'male', 'elderly', 'public flat', and 'single-person household' are important keywords in the management of social relationship capital in Yachiyo City.

### 3.4 Citizens' workshop

Based on the gap between the ideal and reality and the keywords elucidated via the survey, we conducted workshops for citizens to discuss ways to activate social capital. The workshops were conducted twice for middle and high school students ('future workshop') and stakeholders ('stakeholders' meeting').

The 'future workshop' was held in November 2016, and 20 junior and senior high and high school students participated. In this workshop, children, as future mayors in 2040, used results of our survey for their discussions. We explained that 'males have less social capital than females', 'the elderly have less social capital than other generations', 'social capital per person may decline because the elderly population will expand in 2040', and 'people living in flats have less social capital'. In response, the students proposed 'holding resident-participating events in the housing estate', 'setting move-in conditions for a housing estate to let a wide range of generations live there', 'establishing the father's network for child raising', 'preparing a meeting place for the elderly and adults', 'encouraging the elderly to share houses', and 'building a facility where the elderly take care of kids'.

At the stakeholders' meeting in July 2017, 19 people participated. Participants included representatives of local administrative officials, NPOs, community associations, regional industrial organisations, and citizens selected from among applicants. In this meeting, we also explained the results of the resource generator, as was the case with the future workshop.

This meeting featured discussions on how to activate social networks for males, the elderly, flats, and single-person households. In response, the participants proposed 'use vacant houses as share house of various generations', 'create a regional cafeteria where diverse people can interact and hold a lunch party that single-person households and foreigners can participate once or twice a month' and 'build facilities that local people can learn and exchanges'. These ideas are similar to the idea of 'Mehrgenerationenhaus' (multi-generation house) in Germany. Besides that, ideas such as 'operate a fixed community bus to promote people's exchanges', 'built a nursery school complex with an elderly facility' and 'allow health consultation at convenience stores' were provided.

#### **4. CONCLUSION**

In this research, based on the idea that it is important for urban sustainability and resilience to pass on healthy underlying stocks to the next generation, we developed a bottom-up method for managing social capital and applied it to Yachiyo City, Chiba Prefecture, Japan. The developed method is as follows. First, we conducted group interviews among residents to extract important social relationships for the region. Using the results, we created a resource list for the resource generator and grasped the present state of social capital using this list. Finally, we implemented workshops for residents to revitalise social capital.

The results are as follows. First, group interviews revealed that expressive resources are important in addition to instrumental resources. Second, the resource generator survey extracted weak points of social capital in Yachiyo City. Third, at the workshops, several specific ideas were proposed by citizens. From the above, the effectiveness of our method was confirmed.

One of problems is the representativeness of participants of group interviews and workshops. As a method for solving this problem, interviews and workshops should be conducted multiple times. Moreover, group interviews and workshops are greatly affected by the abilities of participants and facilitators. For example, in a workshop conducted for this study, the facilitator could not delve into some ideas sufficiently. There are still many problems regarding how to proceed with the workshop, so we need to improve the facilitation method. In the future, we would like to employ this method in another region to implement improvements.

#### **ACKNOWLEDGEMENTS**

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## 10. TOWARDS RESILIENT OFFSHORE WIND FARMS

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**ABSTRACT.** This paper proposes using a performance-based engineering (PBE) approach to quantify the reliability of offshore wind turbines (OWT), for use in a larger assessment of wind farm resilience. The concept of resilience provides a useful framework for considering an OWT as a system that is comprised of both structural and mechanical components and to extrapolate these risks across a farm. An implementation based on the financial consequence of failure is used here, this allows failure states to be defined that combine analytical structural failure scenarios with empirical mechanical equipment failure rates within a unified calculation of material losses. The loss associated with the failure of each component is used to estimate the total annual loss for a case study farm. Results are presented in the form of a case study and indicate that failure of the structure may have an impact on the overall failure profile of the farm. This method provides a simple estimate of robustness for the farm, which is a component of any resilience assessment. It also provides a foundation from which a more detailed assessment of resilience, including adaptability and recovery, will be developed.

**Keywords:** Offshore Wind, Structural Reliability, Resilience Framework, Loss Modelling, Site Assessment.

### 1. INTRODUCTION

The offshore wind industry has grown to the point where it supplies 11.03GW [1] of electricity within Europe [1], with a further 26.4GW worth of projects approved [2]. Within European waters most existing OWTs are supported on monopile foundations [3]; these are effectively large diameter cylinders that are hammered into the seabed; on top of which is fixed a rotor and tower, a tapered tubular member connecting the monopile to the rotor. However, the overall cost of offshore wind farms (OWF) remains high and a recent UK government report [4] has highlighted “integrated design” as an area that could improve cost reduction. This aim is challenging as OWTs are unique civil engineering structures in that they rely on both mechanical components (such as a generator, gearbox and control system) and structural components (the tower and monopile) in order to remain operational. Additionally, structural design of OWT is undertaken at the component level, with the tower and monopile commonly being designed by separate companies [5]. Prescriptive codes [6], [7] are used to evaluate potential designs but these do not explicitly consider (i.e., through a full probabilistic approach to analysis and design) the risk posed by uncertainties associated with variability in physical properties nor all of the highly variable natural hazards to which OWF are exposed. Safety factors are instead used to achieve a target (structural) reliability level at both component and system level. Any integrated assessment should account for the above uncertainties in an

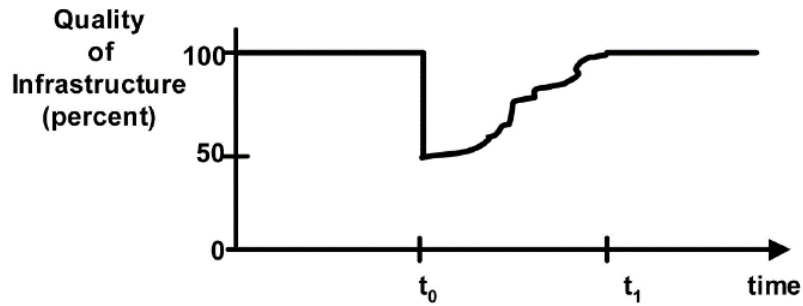
explicit manner, also considering the possible complex interrelations between components; for example, stopping the rotor will change loading on the blades, which will in turn influence loads on the tower and monopile. The problem lies in quantifying the risk posed by these diverse sub-systems and accounting for the impact of failures on the overall operability of the farm.

The concept of resilience provides a framework to consider this problem. It has been used within a large number of fields ranging from design to preparedness of communities exposed to environmental hazards [8] and when applied to structural systems [9] incorporates: robustness, redundancy, rapidity and resourcefulness. These represent the ability of a structure to withstand an extreme event and the time required to re-instate operability afterwards, as indicated on Figure 1. However, the properties are difficult to quantify especially from the perspective of a design stage study, where information regarding the capacity of an organisation to make budget available (i.e. resourcefulness) is unlikely to be available to the design engineer. Therefore, a technique for estimating resilience that only relies on the robustness and redundancy of the structure would allow the concept to be applied at the design stage. The initial design estimate of robustness could be used in a later resilience calculation by the asset operator, which also considers resourcefulness. One approach, investigated by Bruneau and Reinhorn [10], assumes that loss of functionality after an extreme event and the time to recovery are correlated. This is intuitive, as in the general case if an event (i.e. wind storm) causes more damage it will take longer to repair structures as a result. This assumption provides a starting point for considering resilience of OWF and has previously been applied to PBE of structures for blast [11] by defining a relative resilience indicator ( $RRI$ ), which is correlated to resilience ( $R$ ):

$$R(E) \propto RRI(E) = 1/C(E) \quad (1)$$

Where  $RRI$  can be defined as the inverse of the consequence ( $C$ ) of an extreme event ( $E$ ). Under this assumption a structure that experiences a lower consequence (i.e. less damage) as the result of a hazard is viewed as more resilient.

The measure of consequence needs to efficiently capture the impact of failure on the system. An OWT is a system comprised of structural and mechanical components, therefore some typical structural consequence measures are not applicable, such as percentage of the structure collapsing [11]. In this study we relate the consequence of failure to the financial impact of a system failure and specifically material loss incurred by failure. This allows the severity of different sub-systems to be compared by using a single measure which is easy to communicate to different stakeholders but neglects the operational costs of repair, such as hiring vessels, which are expensive but difficult to quantify. Metrics relating to life safety are not of primary importance as the wind turbine is normally unmanned, apart from brief periods for maintenance.



**FIGURE 1.** Graphical definition of resilience after an event (at  $t_0$ ).  
Adapted from: Brunneau et al [8].

A consequence metric based on component material cost requires a probabilistic model describing the likelihood of incurring these losses. The analytical method we apply to model combined losses of structural and mechanical components is discussed in Section 2. This includes a procedure for evaluating failure probability of the structure based on a PBE technique, which employs dynamic structural analysis. The overall calculation is illustrated through a case-study where a farm NREL 5MW OWT has been assessed at a real wind farm site. Section 3 introduces the case study site and describes the structural reliability calculation. While Section 4 demonstrates the loss calculation for the combined OWT system.

## 2. LOSS FRAMEWORK

Loss calculation for an OWT system requires both: information concerning costs of failure and the failure frequencies for all relevant components. In this work we focus on severe failure associated with major repairs or component replacement, and not on routine maintenance or loss of production. Failure of the equipment is relatively common and databases of empirical failure rates exist [12]. However, structural components fail less frequently, and they are designed specifically for each wind farm [5], therefore a site-specific approach is necessary to define average failure rates. This section summarises an approach for calculation structural failures and how these are used in a calculation of system loss.

### 2.1 Structural Reliability

A framework for calculating the probability of incurring different levels of loss arising from failure of an OWT structure has been developed previously by the authors [13]. This considers failure in the turbine's ultimate limit state, i.e., the turbine locally collapsing during storm conditions. A brief overview of the background to the approach is presented here, full details are available in the reference.

The approach is based on PBE which was originally proposed by the Pacific Earthquake Engineering Research (PEER) centre to assess failure of structures due to seismic hazards [14], and the approach has subsequently been expanded to consider a range of hazards including wind [15], [16] and blast [11]. It is based on downgrading risk into conditional distributions that are evaluated sequentially using total probability theorem. This approach can

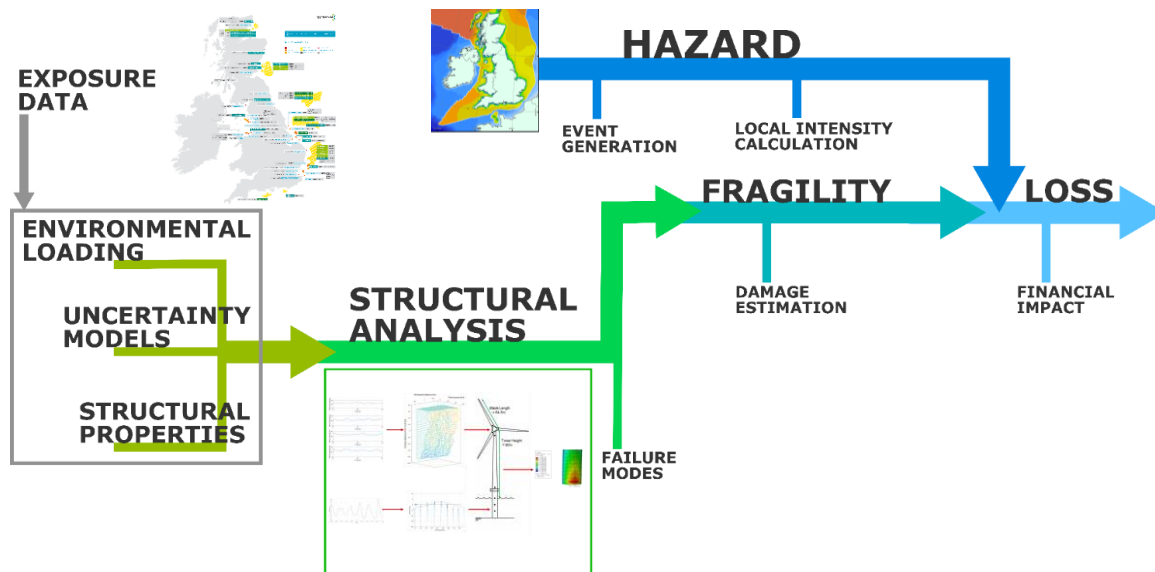


express consequence as expected material loss ( $E(L)$ ) in terms of conditional probability density functions ( $f(\cdot | \cdot)$ ):

$$E(L) = \int \int \int E[L|DM] \cdot f[DM|EDP] \cdot f[EDP|IM] \cdot f(IM) \cdot dDM \cdot dEDP \cdot dIM \quad (2)$$

Where the terms are damage measure (or DM), a parameter describing structural response (engineering demand parameter, or EDP) e.g. a force or stress, and the intensity of a natural hazard (intensity measure, or IM) e.g. wind speed or wave height. This framework can be expressed in a flowchart, see Figure 2, where the individual tasks are:

- Structural (exposure) characterisation – Defining the geometry of the structure, including uncertainties in material properties.
- Hazard analysis – Develop joint probability distribution for environmental conditions, includes wind and wave conditions in an OWF.
- Fragility analysis – Captures uncertainty in mathematical models used to estimate structural capacity and express the probability of damage occurring conditioned on the load intensity.
- Loss analysis – Probabilistic estimate of financial loss, which provides information for deciding whether or not system has sufficient capacity.



**FIGURE 2.** PBE framework for a single OWT structure.

The fully probabilistic formulation indicated by Equation (2) can be simplified by assuming that some of the parameters or models are deterministic, therefore reducing the order of the integration. Specifically, this paper assumes that the damage-to-cost value is constant (all towers are assumed to have the same material cost) for a single limit state corresponding to local failure of the structural components (tower and monopile). Where failure in the ultimate limit state (ULS) is evaluated using deterministic code provisions [13]. Based on these assumptions, the probability of failure required for the full loss calculation can be calculated using only the fragility and hazard components shown on Figure 2, as is shown later in Section 3.3.

## 2.2 System Failure

The wind turbine is modelled as a system comprised of mechanical and structural components. In the general case, a system with independent components ( $N$ ), each of which has discrete failure states, will have a finite number of system failure conditions, i.e. combinations of all the component failure states. These combinations can be summarised in a matrix  $K$  [17] where each individual component has two states, either: functioning or failure, where a value of 1 is used to indicate that the component fails and 0 to indicate that the component remains is operational. The matrix will have entries  $k_{ij} \in \mathbb{Z}^{N \cdot 2^N}$ ; for the 12 OWT components listed on Table 3, the matrix will have entries  $k_{ij} \in \mathbb{Z}^{12 \cdot 4096}$ , where the first column will read  $[0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T$  indicating the case in which all components are functional, and the last  $[1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1]^T$  indicating the case where all components have failed. The intermediate columns contain all possible permutations of 1s and 0s indicating different partial failure states.

If each component has a deterministic material replacement cost, the discrete system failure events can be combined to assess the probability of incurring a repair cost ( $c_r$ ). The matrix of the failure events  $K$  is converted into a failure cost matrix  $K_c$  by multiplying each column of  $K$  by a vector containing the failure cost of each component. This new matrix will contain the same number of elements as  $K$  but the values will equal to the failure cost of each component as opposed to a logical (1 or 0). Then  $P_{sys}(c_r)$  can be defined as the probability that a set of components fail  $k^* \in K_c$  whose combined repair cost is equal to the target ( $c_r$ ):

$$P_{sys}(c_r) = \sum_{k^* \in K_c} \prod_{i=1}^N P_i^{k_i} (1 - P_i)^{1-k_i} \quad (3)$$

$P_{sys}(c_r)$  is summed over all the columns of the  $K$  matrix where the total repair cost of the components equals  $c_r$ , i.e.  $k^*$  is a subset of  $K$  containing all equal cost vectors of system status. The probability of each total material cost is the product of the individual component failure probabilities in the matrix of failure events  $K$  as this calculation assumes each component is independent. When  $k_i$  is 0 then the probability that the component survives is used  $(1 - P_i)^{1-k_i}$  and if  $k_i$  is 1 then the probability that the component fails is used  $P_i^{k_i}$ . The result is the combined probability that a set of conditions (defined by  $k^*$ ) will occur.

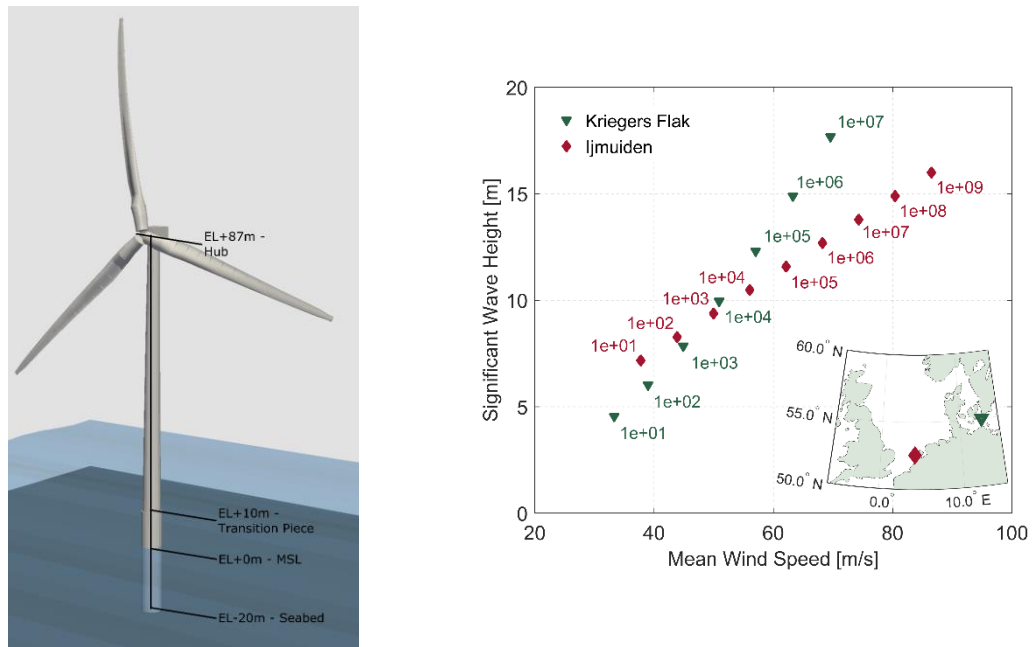
## 3 CASE STUDY EXAMPLE – STRUCTURAL FRAGILITY

An example is used to illustrate applying the loss calculation framework, described in Section 2, to the site of a real-world offshore wind farm. Here resilience is estimated using consequence of failure alone, in the form of financial material costs. The procedure described in Section 2 is implemented in two steps: firstly, fragility curves are defined for a representative, index turbine and, secondly, the loss calculation is performed, using the fragility curves combined with empirically derived equipment failure data. This section describes the fragility calculation for an OWT structural components.

### 3.1 Site Selection and Structural Model

Environmental conditions for the Kriegers Flak OWF site [18] are shown on Figure 3 (right), where mean wind speeds and significant wave heights are plotted against their corresponding mean return period (MRP). The water depth of this is around 20m, making it a suitable location for the NREL 5MW OWT on a monopile foundation, as shown on Figure 3 (left) which has a 30m long and 6m diameter monopile. As indicated on the figure the tower terminates at an elevation above mean sea level of 87.7m. A full list of dimensions and material properties of the turbine are provided by Jonkman et al [19].

The probability of incurring different repair costs was estimated using the calculation described in Section 4.1. The component failure rates for individual turbines were scaled to a farm by multiplying them by the number of turbines, assumed a medium sized wind farm with 80 individual OWT (for comparison Rampion has 116 and London Array 175 turbines [20]).



**FIGURE 3.** Image of the OWT structural model in FAST, with main elevations highlighted (left). Comparison of the extreme wind and wave conditions associated with different MRP at Kriegers Flak [18] and Ijmuiden [21] OWF sites (right), inset map shows the locations of both sites.

### 3.2 Fragility Curves

Fragility curves were developed for the NREL 5MW OWT located at the Kriegers Flak site using MRP as IM parameter by the authors [13] by selecting 16 MRP (as indicated on Table 1) and calculating the probability of failure. At each 400 structural simulations were run where the only statistical variability between the 400 simulation runs is a result of the stochastic wind and wave loading.

A one or zero was assigned to each analysis depending on whether the tower or monopile was predicted to fail during the simulation. The probability of failure was taken to be the mean of this index over all 400 samples, for example a probability of failure of 0.5 is just the average of a vector comprised of 200 ones and 200 zeros. Error in the probability of failure prediction was predicted by assuming that the scatter in probability of failure follows a binomial

distribution [22], which is suitable as each analysis is assumed independent, the probability mass function (PMF) shown in Equation (4):

$$P(x = k) = \binom{n}{k} \cdot p^k \cdot (1 - p)^{n-k} \quad (4)$$

Where  $n$  is the sample size,  $p$  is the probability of failure calculated by taking the mean of the indicator variables and  $k$  is the number of observed failure samples. Based on Equation (4) the variability in prediction of the probability of failure will hold a maximum value when the probability of failure is 0.5 and will be 0 when the probability of failure is either 0 or 1, as the standard deviation will be 0 at these points.

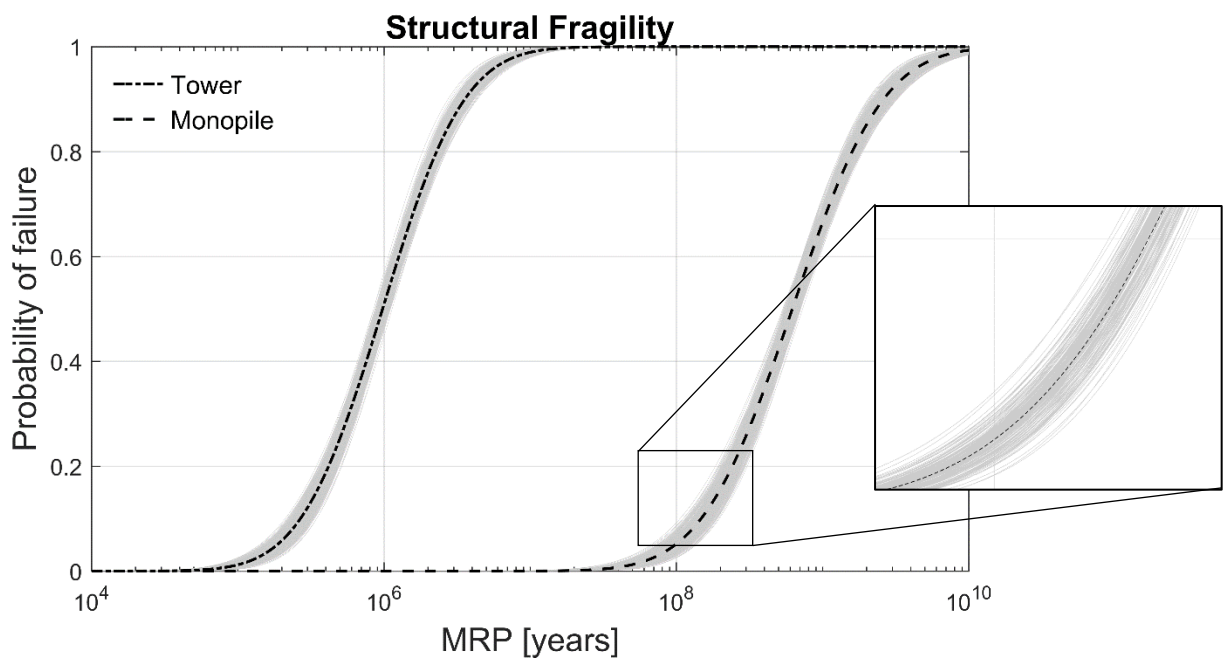
The data on Table 1 was used to fit a fragility curve, which provided a continuous prediction of probability of failure, by using the maximum likelihood estimation to fit a lognormal distribution (which has the parameters log mean  $\mu_{LN}$  and log standard deviation  $\sigma_{LN}$ ). The mean value of fragility is the probability of failure calculated as described in the previous paragraphs, and the best fit lognormal distribution is described by the 'mean' parameters shown on Table 2 with the curves defined by these parameters are shown in black on Figure 4 for both structural components. The MRP in Table 1 were scaled by a factor of 100 when fitting the distribution parameters defined on Table 2 to improve the stability of the fit.

Additional post-processing was conducted to assess the error introduced by using a limited sample size on the parameters of the lognormal distribution. Monte Carlo simulation was used to sampling from each normal distribution at the 16 MRP, using the calculated mean and error as the distribution parameters. The resulting variability in lognormal curves, shown in grey lines on Figure 4, can be used to estimate the variability in the lognormal distribution parameters. This means that the fragility curves for the monopile and tower can be defined as stochastic with both the mean and standard deviation parameters as random variables, as indicated on Table 2. The normality of the lognormal distribution parameters is confirmed on Figure 5, where the four random variables are found to be approximately normally distributed with kurtosis values around 3, per the definition of a normally distribution [23].

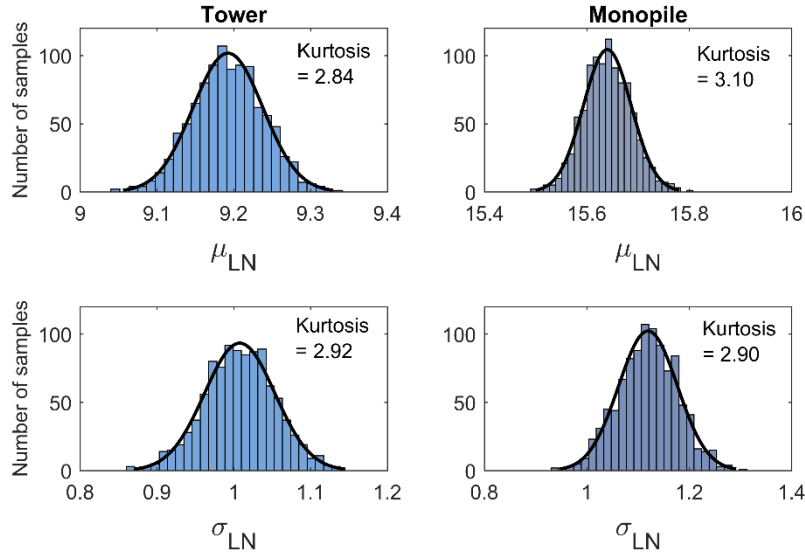
**TABLE 1.** MRP with corresponding probability of failure and standard error for the monopile and tower.

MRP	Pf Monopile	Pf Tower
1.00E+02	0	0
3.00E+02	0	0
1.00E+03	0	0
3.00E+03	0	0
1.00E+04	0	0
3.00E+04	0	0.0025
1.00E+05	0	0.0125

3.00E+05	0	0.13
1.00E+06	0	0.4975
3.00E+06	0	0.8775
1.00E+07	0.005	0.9825
3.00E+07	0.0125	1
1.00E+08	0.095	1
3.00E+08	0.2425	1
1.00E+09	0.6525	1
3.00E+09	0.95	1



**FIGURE 4.** Fragility curves for the tower (left) and monopile (right). The grey lines indicate 100 Monte Carlo samples of from the normal distributions at the 16 MRP used to fit the fragility curve.



**FIGURE 5.** Histograms showing variability in parameters which were used to define the tower and monopile fragility curve. Based on 1000 samples of each normally distributed MRP  $P_f$ . Black lines are the best fit normal distributions.

**TABLE 2.** Random variables associated with the fragility curve fit parameters.

		<b>Tower</b>	<b>Monopile</b>
$\mu_{LN}$	Mean	9.1925	15.6401
	Standard deviation	0.0456	0.0467
$\sigma_{LN}$	Mean	1.0078	1.1196
	Standard deviation	0.0458	0.0574

### 3.3 Structural Component Probability of Failure

As discussed previously, fragility curves represent the expected damage to a component given a level of hazard intensity ( $IM$ ) and can be expressed as a conditional probability of failure ( $G[DM|IM]$ ). However, to combine structural failure with the failure rates of the other OWT sub-systems, we need to convert the distribution into the yearly probability of failure ( $P_f^{Yr}$ ) by applying the total probability theorem:

$$P_f^{Yr} = \int G[DM|IM] \cdot f(IM) \cdot dIM \approx \sum G[DM|IM] \cdot \left( \frac{1}{MRP_i} - \frac{1}{MRP_{i+1}} \right) \cdot dIM \quad (5)$$

In previous work [13] fragility curves for the tower and monopile of the NREL 5MW OWT were calculated at the Krieger's Flak OWF site, the set used in this work are shown on Figure 4. These are based on 10-minute length time-history analyses with MRP is used as the IM; which can be thought of as the inverse of an average rate of exceedance, and therefore the annual probability of occurrence can be summarised using a Binomial distribution as indicated in Equation (4). The annual probability of occurrence was calculated using numerical integration with a step size ( $dIM$ ) of 20 to solve Equation (5).

The mean yearly probability of failure of an individual turbine monopile using Equation (5) is assessed to be  $1.7e-7$  and the tower  $1.7e-4$ , also shown on Table 3, the standard deviation of

both is a factor of 5 times smaller than the mean. This indicates the variability in loss due to statistical uncertainty in the fragility curve is will be small and is therefore neglected in the following analysis.

### 3 CASE STUDY EXAMPLE – LOSS

#### 4.1 Structural Failure Cost

The material cost of the two structural components was calculated independently and are indicated on Table 3, the following paragraph describes the background and assumptions.

Total offshore turbine cost ( $c_{WT}$ ) in k€, including blades and drivetrain but excluding foundations, was estimated using an equation derived by fitting a relationship between turbine costs at seven different power ratings, 2MW through to 5MW, parameterised on the rated power of the turbine ( $P_{WT}$ ) in MW [25]. The equation was converted into Euros by Dicorato et al [26]:

$$c_{WT} = 2.95 \cdot 10^3 \cdot \ln(P_{WT}) - 375.2 \quad (6)$$

Analysis by the National Renewable Energy Laboratory (NREL) [27] reported that cost of the tower of an onshore wind turbine comprised 17.6% of the total turbine cost. We calculate the tower for an OWT cost assuming that the relative cost of components on an onshore and OWT remains constant, using 17.6% of the value predicted from Equation (6).

The OWT foundation cost in k€ ( $c_{FN}$ ) was estimated using a parametric equation [26]:

$$c_{FN} = 320 \cdot P_{WT} \cdot (1 + 0.02(D - 8)) \cdot (1 + 8 \cdot 10^{-7}(h(0.5d)^2 - 10^5)) \quad (7)$$

Where the cost estimate depends on:  $D$  the water depth (m),  $h$  the hub height above mean sea level (m) and  $d$  the rotor diameter (m). The equation originated from a 2003 feasibility study into OWT, and was validated against actual foundation costs from five real OWF. The average error was large, at 8.7%, but Equation (7) was found to predict foundation cost better than two other models derived using fewer parameters [26].

#### 4.2 Equipment Failure Rates and Cost

Failure data for the non-structural components of the OWT were taken from the work of Carroll et al [12]. They analysed data from maintenance records of ~350 OWT ranging from 2MW to 4MW and presented the results for different sub-systems, details of the portfolio are not clear as commercial sensitivity means the data was anonymised. Only the failure rates and material costs relating to the top 10 sub-systems in terms of major replacement cost (out of a total of 19 sub-systems) were used in this work and are shown on Table 3. Additionally, costs were rounded to the nearest €1000, to improve computational efficiency when evaluating Equation (3).

**TABLE 3.** Material cost for major replacement of OWT sub-assemblies.

<sup>1</sup>Equation (6) with data – [ $P_{WT} = 5MW$ ]. <sup>2</sup>Equation (7) with data – [ $D = 20m$ ;  $h = 87.6m$ ;  $d = 126m$ ].

Source	Component	Major replacement [€]	Failure rate [/turbine/year]
Carroll [12]	Gearbox	230,000	0.154
	Hub	95,000	0.001
	Blades	90,000	0.001
	Transformer	70,000	0.001
	Generator	60,000	0.095
	Circuit breaker	14,000	0.002
	Power supply	13,000	0.005
	Pitch system	14,000	0.001
	Yaw system	13,000	0.001
	Controller	13,000	0.001
Parametric equations	Tower	770,000 <sup>1</sup>	$1.70 \cdot 10^{-4}$
	Monopile	2,380,000 <sup>2</sup>	$1.70 \cdot 10^{-7}$
Total Cost		3,762,000	

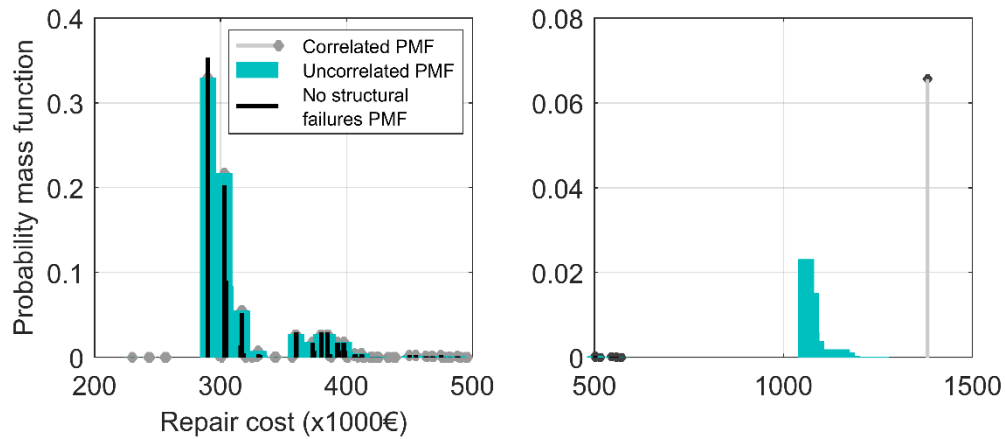
### 4.3 Combined Loss Assessment

The loss estimation was computed using the mean parameters for the fragility curve described in Table 1, therefore the fragility curve has no uncertainty associated prediction of the probability of failure. Three loss calculations are compared:

1. Equipment only, using just empirical data,
2. Structural and equipment components, where all are independent,
3. Structural and equipment components, where failure of the tower causes all equipment to fail and failure of the monopile causes all equipment and the tower to fail too.

The resulting loss profile is shown on Figure 6. Low repair cost failures occur with relatively large probability and these are driven by the more frequently occurring equipment failures, see profile is approximately the same shape for all methods. However, the PMF which excludes structural failures cannot predict repair costs above 1M€ all of which include the tower or monopile. The PMF with independent components predicts a range of failure modes involving the tower, whereas the PMF with combined failure modes only predicts a higher probability larger repair cost. This is more accurate as any failure involving the tower will likely have consequences for all equipment in the hub. The very high repair cost failure at 3,762,000€, which is driven by failure of the monopile in conjunction with other components is not visible due to their rarity, correlated annual failure probability is  $1.331e-5$ . This low occurrence is a result of the MRP at which the monopile begins to fail from the fragility curve, see Figure 4.





**FIGURE 6.** Loss PMF using three calculated using 3 assumptions: only equipment (thin black line), equipment and structure where all components are independent (cyan), and equipment and structure where the failure of the structure results in failure of all other equipment (grey).

## 4 CONCLUSION

The developing concept of resilience provides an alternative approach, which may allow us to consider performance of OWF as a whole. This paper proposes a framework for estimating resilience of OWF by applying the existing framework of PBE. A case study demonstrates how this calculation may be implemented to estimate potential loss associated with the multiple sub-systems present on individual turbines at the OWF level.

In this study, structural resilience is simplified to estimation of the consequence of the turbines failure, which is defined in terms of material cost alone. This allows the idea of resilience to be applied by practicing engineers who will not have access to data required for a full evaluation of resilience, including potential recovery phases. As robustness is a component of a full resilience calculation, the simplified method presented in this paper could be used as an input to a more comprehensive resilience assessment.

The case study presented included both generation equipment and structural. Although structural failure was found to be rare it was associated with very high material costs, which are relevant when considering the overall vulnerability of a wind farm that is comprised of many individual turbines. Additionally, the structure will be site specific, therefore need to include details of site loading into risk calculation, fragility will vary between sites [13].

Future steps will involve considering the risk posed to an array or whole OWF in greater detail, due to correlated hazards i.e. a wind storm effects the whole installation simultaneously. Many challenges remain to be answered, particularly relating to the choice of performance indicators [13]. However, if successful, this approach will aid in the development of integrated design techniques for OWF and therefore works towards meeting the goals set by the UK government cost reduction framework for offshore wind.

## ACKNOWLEDGEMENTS

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# 11. A NEW APPROACH TO PREDICTION OF SATISFACTION: A MEANS TO IMPROVE SUSTAINABILITY AND RESILIENCE OF PUBLIC SERVICES

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**ABSTRACT.** Accurate prediction is critical for reliable public services under changing circumstances. Predictive models constitute cornerstone of simulation tools to identify hazards to for service provision and policies which optimize resource allocation. Real-time predictions can also help with early detection of new problems, to respond to problems earlier or solve problems before they emerge. This study addresses shortages in predictive analytical tools by looking at how to quantitatively represent shifts in public satisfaction in near real-time. Determinants of service user satisfaction are extracted and identified from free-text comments about public services and then used for effective prediction. Furthermore, usefulness of signature method for data pre-processing in a context of a multi-variable prediction is explored. Use of signatures can enable prediction from data points with multiple missing values in a reproducible and automated way. Findings indicate that signatures may reduce model training times several times and allow reliable handling of data points with missing values but with some cost to predictive power. Public institutions can make use of signatures for real-time predictive analytics in scenarios of numerous missing data, to enable near real-time analysis of public opinion trends without need for labour-intensive data imputation and pre-processing.

**Keywords:** Determinants of Satisfaction, Financial Sustainability, Prediction, Signature Method

## 1. INTRODUCTION

At present, the difficulty of processing and analysing data makes it impossible for public organisations to reliably use predictions in decision-making [1–4]. Public managers lacking reliable simulation tools may find it harder to make financially sustainable investments in services whilst enabling a flexible response to shocks impacting on service provision. Accurate prediction of future trends may be especially difficult when data used for training the prediction model is not very abundant and where the prior pattern in the time series has not been smooth. The data may be ‘rough’ over time. Examples of such rough data paths over time include patterns in satisfaction ratings from public services by service users. Prediction into the future from sparse and rough path readings may require pre-processing of predictor data before a model useful for informing decision-making is computed. At present, the procedure for preparation of such data often depends on the experience and opinion of the researcher and may not be reproducible [5]. Development of more automated and hence reproducible methods for pre-processing of rough and sparse time series data may be advantageous. Signature method is one potential approach for handling automated pre-processing of rough time series records [6]. Prior studies have explored the usefulness of signatures for prediction [6,7] but so far an exploration is missing into whether signatures can also be helpful for multi-dimensional regressions from sparse data. This study introduces and investigates the

usefulness of the signature method for a prediction task, on example of predicting satisfaction with general practice (GP) medical services funded by National Health Services in England. Enabling analysis of sparsely provided written feedback to identify key trends in near-real time would greatly enhance the capability of NHS managers to respond to unexpected issues with service provision on both national and local level. Accurate prediction of anticipated issues with service provision would constitute an early signalling mechanism for problems before they affect the quality of delivered services. Predictive models trained on user feedback may also serve as simulation tools for identification of optimal policy decisions, as well as hazards which may disrupt services for end users.

Usefulness of the signature method for prediction of satisfaction with GP services is tested with Lasso regressions implemented with Python programming language<sup>15</sup>. Lasso regression models have been computed in different configurations of independent and dependent variables. Lasso regressions trained on unprocessed predictor data were compared to the same model trained on the same data pre-processed into signatures. Outcomes of analysis indicate that signatures may be used for high-speed computation of effective predictive models which take into account why service users are satisfied. Moreover, signatures enable use of incomplete data for model training in a systematic, reproducible manner.

## **2. LITERATURE REVIEW**

Decision-makers in public organisations may decide better when they are informed about likely consequences of their decisions, and may act quicker to overcome service delivery issues if necessary insights are available earlier. Hence, prediction of possible consequences of decisions and early detection are among key analytical priorities of any public organisation [8]. They should be done in anticipation of likely events, such as shifts in intensity of use of services, as well as to identify risks of rare, highly disruptive events such as extreme weather [1,8,9,10]. Heeding user feedback is critical for effective predictive analytics. Users of services to a large extent define the problems which need to be solved and determine relative importance of specific issues. If public organisations heed end users' feedback, they can develop sounder service provision approaches [11–13] and choose more aligned and effective funding priorities [12,14,15]. For example, public healthcare organisations that pay attention to patients' opinions and gain their trust are able to, without significant additional funds, improve treatment rates for preventable diseases [16–18]. Patients are more likely to report truthful testimonies of their symptoms to doctors if they trust their healthcare provider [16–18]. Advances in measurement of public opinion are necessary for more accurate prediction of quality of public services in the future [3,19].

Means of assessing user satisfaction at present are often deficient. Many public organisations tend to estimate it with proxy values which may be loosely connected to what is supposed to be measured [20–23]. For example, treatment rates for specific diseases may substitute citizen opinions as measures of their satisfaction – regardless of the methods employed to treat patients or their effectiveness [24]. Public organisations tend to use available data to quantitatively study only the behaviour of service users without trying to simultaneously

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<sup>15</sup> Lasso regressions have been implemented with Scikit Learn library. More information is at: <http://scikit-learn.org>, last visited on 21st Aug. 2017

understand the reasons for it [4,19,24,25]. Any such predictions are highly unreliable [9] and hence it is usually not possible to simulate organisational change while considering all relevant social interactions and contexts [1–4, 10]. Especially concerning is inability to accurately predict user experiences of public services on individual level, which is necessary for more tailored provision of services which takes into account individual circumstances whilst treating individuals fairly [3,19]. Surveys are a popular quantitative approach to summarising opinions [26] and serve as a means of addressing the shortcoming of formal performance evaluations. Surveys help investigate why are users satisfied with public services [26]. At the same time, surveys are not suitable for near real-time, highly accurate predictions because there are no financially viable, established methods to use them for continuous measurement of satisfaction under changing conditions [27–30]. Each time when circumstances of data collection change, the survey questionnaire needs to be adapted, which makes it difficult to observe long-term trends. It is also impossible to measure satisfaction continuously in most instances because the costs of the procedure would be prohibitive. Furthermore, feedback received through restricted lists of survey questions tends to oversimplify the reasons for user satisfaction [31,32] and may be biased in not fully predictable ways by survey structure [26,29,30]. Therefore, both practitioners and scientists encourage introduction of other forms of data beyond surveys to more effectively gauge the determinants of user satisfaction with public services [31,33–35]. Griffiths suggests recommender systems are a suitable approach to model individual differences between service users [2]. However, the approach he suggested by default relies on behavioural patterns of users to train the model for prediction [2]. Rationale of service users for specific behaviours should be considered as well as their behaviour to make more reliable predictions of future behaviour. Another challenge when designing new measures of opinion about public services is the complexity of data structures that may be required. A common recommendation for more powerful predictions is to obtain more high quality datasets which incorporate more variables [1,4,19]. The challenge of the approach is that obtaining, merging and processing more data necessitates significant investments [1,4,10,25x]. Significant costs of innovation would inevitably slow down intake and value-added of new solutions in public institutions. Moreover, it is never certain that some important variables are unknown or may be unobtainable. In all, new modelling approaches need to be deployed to deal with currently intractable modelling issues.

Feedback collected from citizens interested in improving public services is a candidate resource for bringing additional insights for predictive models. Free-text reviews of users offer more comprehensive insights than user surveys and are cheaper to obtain [26x, 5]. They have no restrictions on what issues to cover, and feedback can be provided any time. Bates et al give examples of communities formed on social media to comment about treatment of specific rare diseases for the purpose of rating healthcare services [26x]. Data from communities organised around interest in improvement of public services may help support sustainability and resilience of public organisations [1]. Public availability of feedback used for predictions, if coupled with easy-to-understand models, enables more direct public influence on how public resources are allocated [1,3]. Furthermore, analysis of data from communities may support introduction of shared decision-making with citizens about public services [1,3]. Co-creation of services tends to significantly improve sustainability and resilience of public services because those organisations learn and adapt faster this way [1].

One major problem with free-text comments is that service users post their comments irregularly. Public service providers being assessed may also receive no feedback in some

periods. Sparse datasets with such problems may be difficult to trim down and pre-process, and many instances of interest may end up being excluded [5]. In the case of Miotto et al, for instance, data sparsity forced the authors to remove 99% of available information. For the 1% of information they chose to retain on the basis of their experience, they employed dataset-dependent strategies to fill out missing values [5]. Miotto et al's data cleaning process is not fully reproducible and transferable to other contexts despite robust descriptions. Furthermore, the resulting model may not be useful for predicting future values for data points with incomplete predictor information. Data sparsity makes quantitative studies harder to implement and less reproducible. Fortunately, there are opportunities to address the problem of data pre-processing. One way to cope with data sparsity is to use signature method to transform variably sparse time series information into signatures of equal length [7,36]. Signatures are obtained by reducing non-linear relationships between data dimensions into lists of linear relationships [6,7]. A signature of data available for a data point is an infinite sequence of ordered iterated integrals [36]. For modelling purposes, only first terms of the sequence up to a selected level of integral iterations are used as features for model training [36]. Missing values do not disqualify a data point from being processed into signatures as long as it has a full set of values recorded on each dimension at least two times, both for independent and dependent variables [7,36]. Moreover, models computed from signature-processed data may be computed at a relatively lower computational cost and be more accurate compared to models from the same but unprocessed data [6,7,37]. Thus far, published examples of use of signatures relate to classification problems [37] or regression problems with 1-dimensional time series data [7,38]. Relative performance of signature-based models for predictions using regressions with multi-dimensional predictor space is not certain. Therefore, a research question of this study is: Does a signature-based prediction have any advantages over a non-signature-based prediction of satisfaction of users from public services? Answers to this research question could enable more accurate predictions of satisfaction, which may be helpful for increasing long-term sustainability and resilience of public sector service providers. Moreover, it would also showcase how subjective user narratives can be consistently included in quantitative simulations of organisational change, also in near real-time.

### 3. METHODS

Usefulness of the signature method for prediction is tested with anonymous reviews of GP health services funded by National Health Service (NHS) in England<sup>16</sup>. The dataset used for prediction has been generated from 145,000 of GP service reviews posted from May 2013 until January 2017. Each review contained a record of when it was posted, a free-text comment and Likert-scale star rating responses to 6 statements: 1) "Are you able to get through to the surgery by telephone?", 2) "Are you able to get an appointment when you want one?", 3) "Do the staff treat you with dignity and respect?", 4) "Does the surgery involve you in decisions about your care and treatment?", 5) "How likely are you to recommend this GP surgery to friends and family if they needed similar care or treatment?", and 6) "This GP practice provides accurate and up to date information on services and opening hours". The text comments from all reviews contain narratives accompanying the choice of Likert-scale

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<sup>16</sup> The reviews are collected and managed by NHS Choices. More information is at: <http://www.nhs.uk/aboutNHSChoices>, viewed on 11<sup>th</sup> September 2017

responses. They were analysed with LDA topic model<sup>17</sup> [39] to generate 57 topics. The resulting topics represent key themes present in the reviews which were then clustered with a community detection algorithm to produce a cluster of positively-associated topics such as “great doctors” and “professional”, a cluster of negative topics such as “long waits” and “bad facilities” as well as a cluster which grouped neutral topics<sup>18</sup>. Information on proportional presence of positive and negative topics in each GP review was used in further analysis. The proportions of positive and negative topics were combined with ID numbers of the Clinical Commissioning Groups (CCGs) which disbursed funds to the GP services commented on in each review<sup>19</sup>. Furthermore, two variables were added to the dataset which could affect satisfaction with GP services: average level of deprivation of patients registered at the commented-on GP practices and the number of patients registered at the commented-on GP practices<sup>20</sup>. The combined dataset was then transformed into a panel format. The resulting panel data were organised according to 209 CCGs to which commented-on GP practices belonged, and each CCG had a path of data (grouped into monthly time stamps) which included up to 45 recordings. Each recording in the panel dataset was a monthly summary of feedback about GP practices funded by a given CCG. The recordings contained: average level of patient deprivation, average size of GP register in commented-on GP practices and a count of reviews in a given month. 40 CCGs had fewer than 45 recordings due to lack of reviews in some months and were removed from the dataset. Removal of incomplete data paths enabled like-for-like comparisons of models trained on signature-processed data and unprocessed data.

The data paths summarising feedback about GP services sponsored by 169 CCGs were modelled with Lasso regressions to answer the research question about the relative utility of the signature method for multi-dimensional prediction. Lasso regressions were used because they allow for a non-parametric choice of the best model from the available predictor variables. Each Lasso regression was implemented with a 5-fold cross-validation with the same randomly selected training and test datasets, and was trained with up to 10,000 iterations. The number of reviews in each month as well as average monthly levels of deprivation, GP register size and proportions of negative and positive topics were normalized (on a scale from 0 to 1) and used as independent variables in predictions. 5-point Likert-scale responses to the 6 above-mentioned survey statements were used as dependent variables. Lasso regression models were trained for prediction as in this example: To predict month 38 from a 10-month-long data path of independent variables 2 months in advance, the Lasso regression model was trained on dependent variable data for month 37 and independent variable data from months 26-35. Tests of the trained Lasso regression model were carried out using predictor data for months from 27 to 36 to predict for satisfaction in month 38. The same set of

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<sup>17</sup> Further details about the stm software library used in R programming language for implementation of the topic model are available at: <https://CRAN.R-project.org/package=stm>, viewed on 6<sup>th</sup> February 2017

<sup>18</sup> Topics have been clustered with Gephi, a software package for network modelling. For further information please visit: <http://gephi.org>, viewed on 27<sup>th</sup> February 2017

<sup>19</sup> Source: <http://content.digital.nhs.uk/catalogue/PUB18468>, last visited on 1<sup>st</sup> August 2017

<sup>20</sup> Counts of patients registered from each area of England (LSOA, Lower Layer Super Output Area – about 300 households per area) in GP practices in England were merged with data on levels of deprivation at each LSOA. Both datasets contained information for 2015 and were obtained on 1<sup>st</sup> August 2017. Patient counts per LSOA were obtained from <https://data.gov.uk/dataset/numbers-of-patients-registered-at-a-gp-practice-lsoa-level>, and data on deprivation per LSOA was obtained from <https://www.gov.uk/government/statistics/english-indices-of-deprivation-2015>

dependent and independent variables was used to make predictions with independent variables which were either unprocessed or transformed with the signature method. The signature method was used to compute both signatures or log signatures of predictor path for the 169 predictor data paths. (Log)signatures are simplified representations of the paths which contain path properties [36]. They have been computed with esig library, a software package for python programming language<sup>21</sup>. esig computes signatures up to a specific degree. Maximum degree of the signature constrains its length, effectively constraining the level of detail with which the properties of the path are represented through a (log)signature [36]. The higher the maximum degree, the longer the (log)signature [36]. For an all-in-one explanation into how signatures and log signatures are calculated please refer to description by Reizenstein [40].

The first task was to establish in which cases do Lasso regression models predict satisfaction most accurately from narratives about public services, without transforming them with the signature method. Sets of Lasso regressions were trained to obtain mean squared errors (MSE) of test predictions for all 6 dependent variables in months 41 through 45. The models were trained to predict up to 15 months ahead with predictor paths of length from 2 to 25. A combination of predictor path length and number of months ahead with the lowest prediction test MSE was to be found. Once the best combination has been found, Lasso regressions were computed with it involving both signature-processed and unprocessed data. MSE prediction errors for the test months (41 through 45) as well as computation times were recorded. Lasso regressions involving signature-processed predictor data were carried out with signatures (from 2 to 4 degrees) and log signatures (also from 2 to 4 degrees). Several alternative (log)signatures were used to evaluate if longer (log)signature representations of independent variable data improve test prediction accuracy. The resulting models were then compared in terms of the computing speed and test prediction MSE.

## 4. RESULTS

Lasso regressions were computed with unprocessed data to test prediction accuracy for 6 dependent variables in months 41 to 45. Predictor paths from length 2 up to 25 were used to predict up to 15 months ahead. Table 1 includes average mean squared prediction errors for each combination of predictor path length and month ahead. Longer paths used for prediction yielded relatively more accurate Lasso regression models than shorter paths. Shortest-term (1-2 months ahead) and longest-term predictions (10-15 months) with long predictor paths were the most accurate. Furthermore, most dimensions in all trained Lasso regression models had 0 or near 0 coefficients for the majority of independent variables. Of all models, prediction 15 months ahead with a path of 24 months yielded the most accurate model with 0.410 test MSE error, and prediction 3 months ahead with path of 3 months yielded the least accurate model with 0.464 test MSE error. The combination of 24-month-long predictor path predicting 15 months ahead was chosen to test the relative utility of pre-processing data into (log)signatures for prediction.

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<sup>21</sup> For more information about esig please visit: <https://pypi.python.org/pypi/esig>, viewed 11<sup>th</sup> Sept 2017

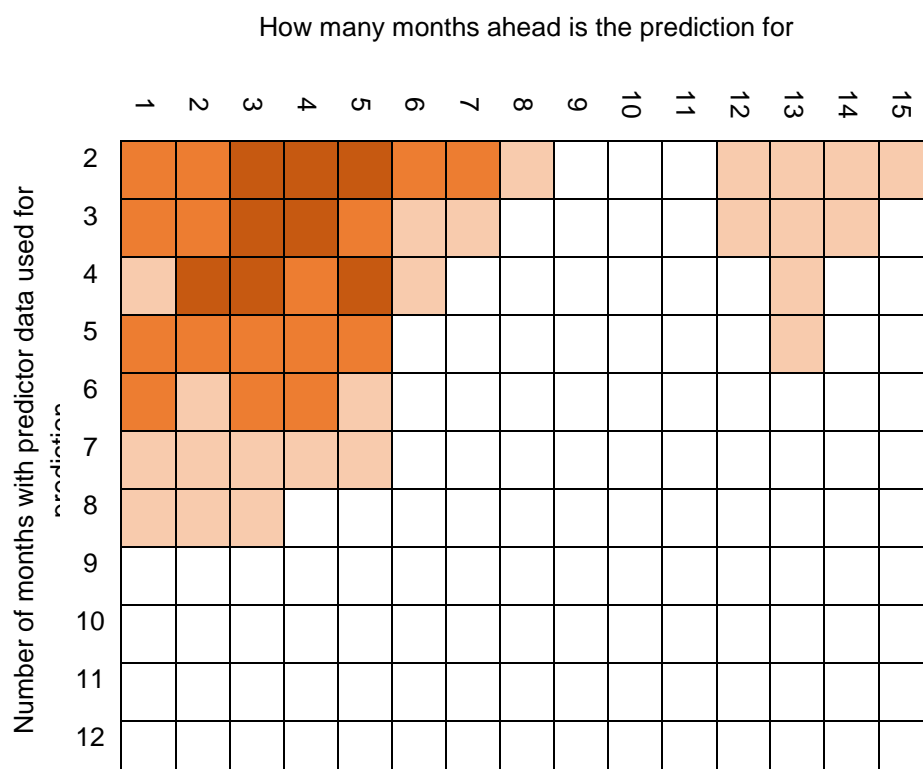


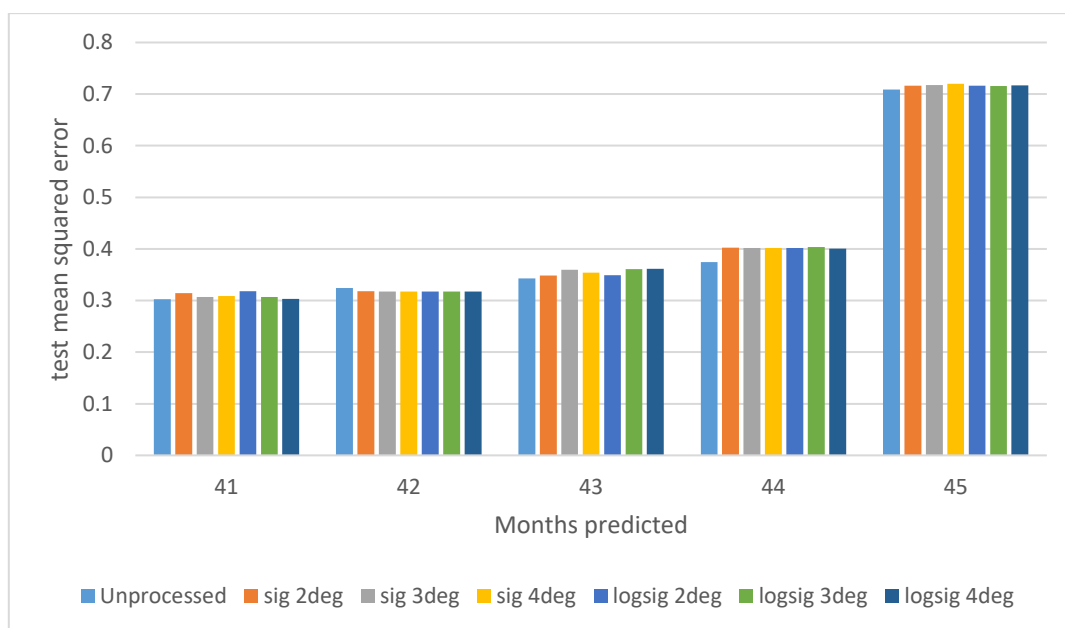
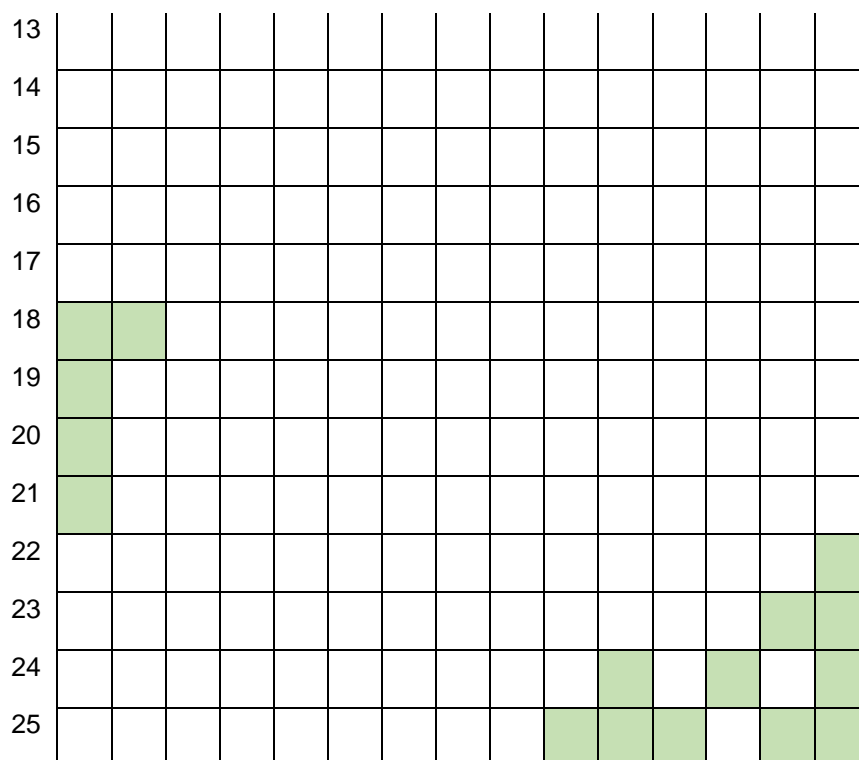
Lasso regressions trained on signature-processed predictor data for months 41 through 45 appear to offer no advantage relative to Lasso regressions trained on unprocessed data (see Figure 1). On average, Lasso regressions trained on unprocessed data had a 0.41 test MSE prediction error, and the second best average was obtained from 2-degree signature-based Lasso regressions with 0.42 average test MSE error. Signature-based and log signature-based Lasso regressions outperformed Lasso regression on unprocessed data only in case of prediction of the dependent variables in month 42. Predictions for month 45 stood out as overall the most difficult to predict, potentially because the data collection of feedback from this month included only reviews posted up to 12<sup>th</sup> day of the month (the day when data scraping was concluded). Overall, prediction accuracies between models were broadly similar for each of the months.

**TABLE 1.** Average test mean squared errors with Lasso regression models trained from unprocessed data

Notes:

- The table reports averages of mean squared errors for test prediction of 6 dependent variables in months 41, 42, 43, 44 and 45
- Lasso regression models are trained with independent variable data from preceding months, using predictor data from 2 up to 25 months.
- The models were trained to predict from 1 up to 15 months ahead
- **Green** shading indicates the test prediction is more than 1 standard deviation more accurate than average of test predictions reported in the table. **Light**, **medium** and **heavy** red headings indicate, respectively predictions which are 1, 2 or 3 standard deviations less accurate from average test prediction. Average test mean squared error was 0.425 with a standard deviation of 0.09.



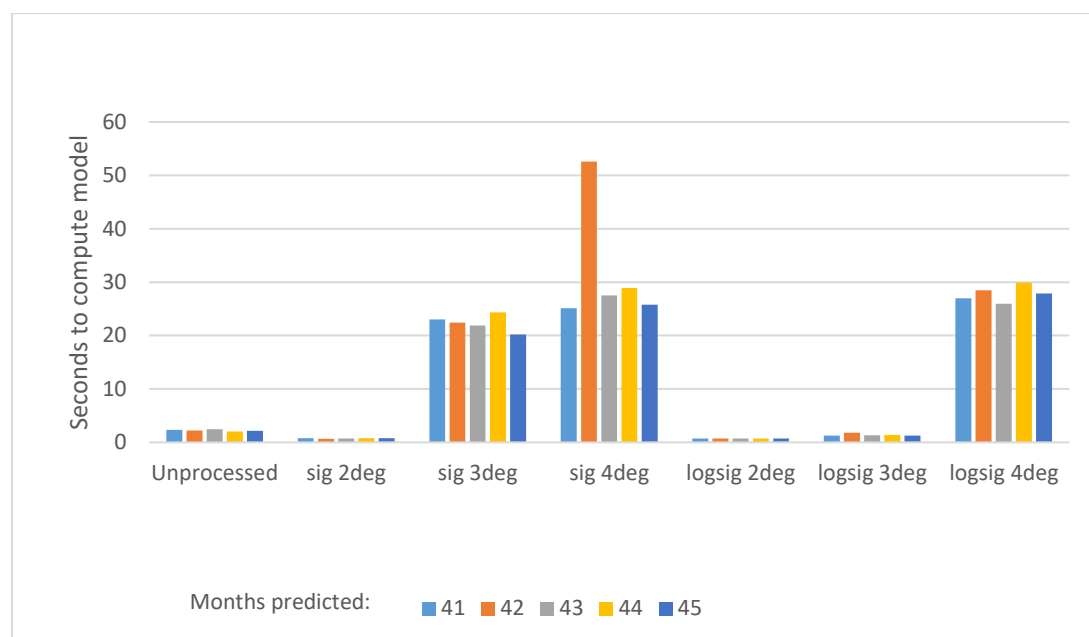


**Notes:**

- The table reports averages of mean squared errors for test prediction of 6 dependent variables in months 41, 42, 43, 44 and 45
- Seven lasso regressions were trained for prediction with unprocessed data and with the same data processed into signatures (from 2 to 4 degrees) or log signatures (from 2 to 4 degrees)
- The models were trained to predict 15 months ahead from 24-month-long predictor paths

**FIGURE 1:** Average MSE test errors for Lasso regressions using variants of independent variable data

With regard to computational time, however, Lasso regressions trained with data processed into 2-degree signatures as well as 2-degree and 3-degree log signatures had an advantage over the baseline Lasso regression. Table 2 reports how many seconds it took to train and test different Lasso regression models. Lasso regressions trained with 2-degree log signatures were the fastest to compute on average in 0.72 s on average, followed by 2-degree signature-based Lasso regressions computed in 0.75 s on average. Lasso regressions from unprocessed data took 2.23 s to compute on average. Higher-degree (log)signatures cause Lasso regression to compute much more slowly.



Notes:

- The table reports average computing times for test prediction of 6 dependent variables in months 41, 42, 43, 44 and 45
- Lasso regressions used for prediction were trained with either unprocessed data and with the same data processed into signatures (from 2 to 4 degrees) or log signatures (from 2 to 4 degrees)
- The models were trained to predict 15 months ahead from 24-month-long predictor paths

**FIGURE 2.** Average model training times for Lasso regressions using variants of independent variable data

## 4. PREDICTIVE PERFORMANCE OF SIGNATURES

Findings indicate that prediction of future satisfaction scores with public services can be effectively carried out from text data containing user opinions. At the same time, comparison of Lasso regressions trained on signature-processed and unprocessed data reveal that conversion of predictor paths into signatures and log signatures does not improve prediction accuracy as opposed to previous examples provided in literature [6,7,37]. The reason for that may be that the other examples of use of signatures involved ordinary least squares regression as the basis for model comparison [7], or because the data transformed into signatures was pre-processed previously and the baseline models were trained on value increments over time rather than on absolute values [6,7]. Moreover, more complex

representations of the predictor data through higher-degree (log)signatures did not improve test prediction accuracy over simpler (log)signature-based representation. The reason for lack of improvement with more complex data representations may be a consequence of small overall dataset size (169 data paths) and relatively short paths used for model training [7].

In support of using (log)signatures for prediction in the future, computational time of predictive modelling may be reduced several fold with the help of lower degree (log)signatures. Superior model performance may be critical in contexts where fast model or efficient model training is key. Another advantage of processing data into (log)signatures is that prediction quality is still broadly comparable to that of a model involving unprocessed data whilst at the same time enabling use of reproducible, more automated means for inclusion of data points with missing values in model training. Even data points with missing dependent variable values can be included in the dataset used for modelling if the dependent variable data are turned into signatures [36]. At the same time, however, addition of data points with missing values may decrease overall model accuracy. For example, data may be missing non-randomly in a sparse dataset that contains relatively less information per data point [37]. Therefore, if data points with missing values are used for modelling, it is advisable to add information on missing data into the model. For example, an independent variable containing a count of missing records in a data path turned into signature may improve the accuracy of a regression model. In consequence of uncertainty with regards to the reasons for missing data, full automation of data pre-processing with the signature method is not advisable. The limitations of the available data for predictive modelling should be considered [8] but nonetheless signatures enable more swift and reproducible means of pre-processing sparse data.

Future work with regards to this study may explore a change of the model used for comparison between signature-processed and unprocessed data. Lasso regression may be less useful than elastic net regularization. This is because the best predictions with Lasso regression tended to handpick a small number of independent variables, hence potentially leading to overemphasizing the importance of predictor values in specific months in model training. Furthermore, incorporation of past satisfaction scores into model training may help explore if the narratives add value in terms of improving prediction accuracy. It would be possible to answer in more detail when, how and why how narratives used to justify satisfaction with public services could be included in simulations of effects of organisational change in the future.

## **5. CONCLUSION**

The study has established that measurement of satisfaction with public services with help of narratives expressed by service users through free-text reviews is technically feasible and may be useful for boosting sustainability and resilience of public organisations. Quantified user narratives may help estimate real-time impacts of change on perceptions of service quality, and may help shed light into evolving expectations of citizens. As a result, decision-makers may obtain access to a rich information resource which they can use to ensure financially sustainable service provision amidst changing circumstances, by considering the voice of the public in the decision-making process. Accurate predictions which take into account the reasons for satisfaction of service users may also be used in the future to simulate effects of planned reforms. Candidate reforms with the highest potential for improving the quality of public services can be identified and compared along measurable criteria. Moreover, it was found that signature method may be highly useful for training efficient and comprehensive

predictive models involving sparse data. The addition of data points may be important especially when data are likely missing at random in the dataset. Findings from a trained model predicting only from data points with no missing values may be biased without cases with incomplete data records.

## ACKNOWLEDGEMENTS

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## 12. MICROBIAL FUEL CELLS FOR THE MICRO GENERATION OF ELECTRICITY AND BIOMETHANE FROM ORGANIC WASTE.

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**ABSTRACT.** Microbial fuel cells (MFCs) can be used to treat contaminated water and produce a small electric current in the process. Their main advantage against the traditional waste water treatment (WWT) process, is that they can operate anaerobically (displacing the need and cost of aeration) and they produce less sludge per unit of organic waste treated. Anaerobic microorganisms called methanogens are able to produce methane gas as by-product of their metabolism. On the other hand, microorganisms called electrogens are able to directly transfer electrons to the anode of a MFC. Some studies suggest that electrogens and methanogens develop syntrophic relationships, through direct hydrogen and electron transfer that benefit both microorganisms. The last suggest that the anaerobic treatment of organic matter using MFCs could lead to the production of electricity and higher methane yields. Our research explores the idea of combining these two technologies for the treatment of organic waste.

**Keywords:** Cogeneration, methanogens, electrogens, syntrophic relationships.

### INTRODUCTION

Microbial fuel cells (MFCs) are extremely simple devices that can recover electricity directly from the organic matter contained in waste water (WW)<sup>1</sup>. They consist of an anode and a cathode, held in a container with or without a membrane separating them. The most popular materials used for the electrodes are graphite (anode) and steel (cathode), and for the membrane the most exiting materials being used at the moment are ceramics. There is a vast amount of energy contained in the organic waste disposed of daily by the domestic, industrial and agricultural sectors all around the world. At present, waste water treatment (WWT) facilities are designed in a way such that they demand energy instead of producing it, which constrains their use. MFCs use the contaminated water as electrolyte to power a small current, normally in the range of mA. Under laboratory conditions and pilot scale trials, It has been shown that they can remove up to 90% of the chemical oxygen demand (COD) of domestic waste water<sup>2</sup>. Additionally, one of the main costs within the WW treatment process is the aeration of the WW during the biological treatment phase. MFCs can treat water anaerobically, reducing the need of the aeration process without prolonging the retention time<sup>1</sup>. Moreover, the biomass production yield under anaerobic metabolism is lower than under aerobic conditions; 0.07 – 0.22g per g COD initial against 0.4 g per g COD initial. Therefore, less sludge is produced and because of this there is potential to reduce the cost of its disposal<sup>1</sup>. Microbial fuel cells (MFCs), as other types of fuel cells (FCs), are electrochemical converters (also called bioelectrochemical devices BEDs) that release (as an electric current) the energy that is stored in a fuel molecule. The main difference between MFCs and other types of FC



(such as Proton exchange membrane fuel cells PEMFC) is that MFCs use microorganisms called electrogens, to mediate the transfer of electrons from the organic molecule (fuel) to the fuel cell anode. MFCs, can accept a wide range of molecules as fuel, which includes organic substances like carbohydrates, organic acids, lipids, amino acids and molecular hydrogen. They do not require a purified fuel and can accept a mixture of organic molecules. This possess has an advantage against PEMFC that require pure hydrogen or methane. At present the majority (95%) of hydrogen produced globally comes from (unsustainable sources such as) steam reformation of fossil fuels<sup>3,4</sup>. BEDs like MFCs and microbial electrolytic cells (MECs) can recover electricity from organic residues and also produce hydrogen that could be later used in a PEMFC<sup>5-7</sup> to make a transition towards a sustainable source. The main constrain for the commercial development of MFCs is the low electricity yields that can be recovered from the organic waste. While PEMFCs can be deployed to generate substantial amounts of energy, such as that needed to power a car or to provide electricity to a building, MFCs electricity output is in the range of few watt per square meter of electrode<sup>2</sup>.

Anaerobic metabolism is less efficient recovering energy than the aerobic one. During glycolysis only two molecules of Adenosine tri-phosphate (ATP) are formed anaerobically, while 32 are formed under aerobic conditions. The last has an impact over the (retention) time used by the microorganisms to consume the organic matter (OM) of the WW within the biological reactors during the WW treatment process. Aerobic microbes can eat faster but they also reproduce faster and build up more biomass (sludge). Anaerobic digestion (AD) is limited to the metabolism of organic waste in much higher concentrations, where the longer retention time period is compensated by the production of hydrogen and methane. At present within WWTF, AD is used only at the end of the biological process, to recover energy and fertilizers from the activated sludge produced. This work explores the idea of integrating the use of MFC and the anaerobic digestion of organic matter for the parallel production of biogas and electricity.

## **AIM AND OBJECTIVES**

The aim of our work is to analyse the feasibility of integrating a microbial fuel cell and an anaerobic digester, trying to predict possible outcomes for the production of biogas and electricity and finally proposing a design to test the integration of both systems.

## **METHODOLOGY**

### **Desk based analyses**

#### **Biochemical Pathways**

A review of the main metabolic pathways for the production of electricity and biogas was developed in order to identify possible interactions between the different microbial communities within the AD reactor.

#### **MFC configuration**

Different MFCs configurations were reviewed to identify the optimal system set up which will allow scaling up in the future. Different electrodes materials are compared based on their efficiency to produce electricity and the cost of their use, with a focus on low cost materials. Based on the MFCs configuration and materials analysis, a dual AD\_MFC system will be proposed to be tested through laboratory analyses.

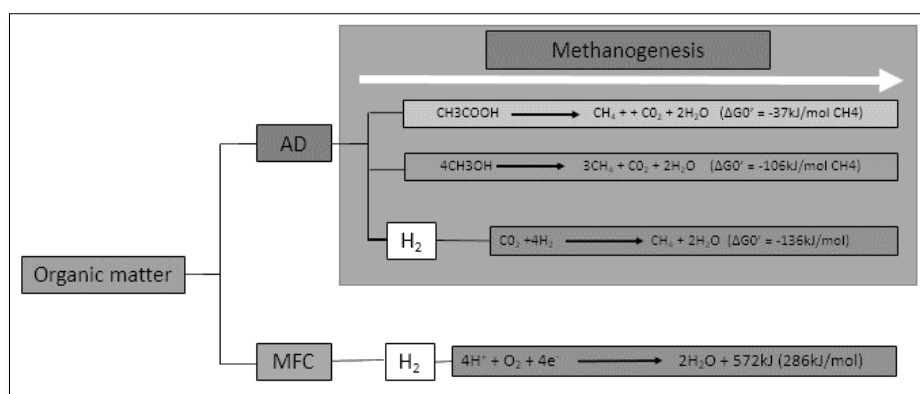
## RESULTS

### Metabolic pathways

Living organisms can be classified in autotrophs and heterotrophs, the first ones are able to store in the form of complex organic molecules the energy obtain from a light source (photosynthetic) or a chemical source (chemosynthetic). Plants and microalgae are examples of photosynthetic autotrophs and methanogen microorganisms are an example of chemosynthetic autotrophs. Heterotrophs on the other hand, are not able to capture energy and are required to steal the energy stored in organic molecules by autotrophs to power their own metabolism. The process of capturing energy and storing it in organic molecules is called synthesis, while the opposite process where the energy from organic molecules is realised, is called respiration. During the respiration process, hydrogen from organic compounds such as hydrocarbons, is separated and transported by carrier molecules such as NADH to the cell membrane. Here the hydrogen's electron is passed through the electrons transport chain where is used to move the corresponding proton outside of the membrane in order to create a proton gradient. These gradient is used to power the production of ATP from inorganic phosphorus (Pi) and ADP. ATP is the energy currency from the cell and it is used to power cell reactions which require energy. The driving force that allows the formation of ATP is the electronegative attraction between the protons and electrons to the final acceptor of electrons. Aerobic organisms use oxygen as the final electrons acceptor, we combine hydrogen from food with oxygen and produce water. Anaerobic organisms can use other molecules instead of oxygen as final acceptor of electrons. Electrogens is the name given to microorganisms that can use a metal such as iron as a final electrons acceptor. Within a MFC the anode electrode acts as a final electrons acceptor for electrogenic microorganisms.

Several possible interactions between the microorganisms present in an AD reactor and those in a MFC have been identified. The AD of organic matter can be separated in four main steps, hydrolysis, acidogenesis, acetogenesis and methanogenesis. This series of consecutive steps take place under anaerobic conditions and are the result of the syntrophic relationships between different types of microbial communities. These microbial communities use the energy derived from the metabolism of organic matter to cover for their cell energy requirements. During the first step of AD process organic matter is broken down from large molecules into smaller molecules (hydrolysis), the next two steps are the formation of organic acids and finally the formation of acetate. The metabolism of glucose and the metabolism of fatty acids through beta oxidation leads to the production of the two carbon molecule acetate and carbon dioxide. These steps are performed by fermentative microorganisms that are able to convert sugar in acetic acid. A different group of microorganisms called Archaea are capable of producing methane from the by-products released by the fermentative microorganisms. Depending on the molecule they use as fuel they can be classified in acetoclastic, methylotrophic and hydrogenotrophic methanogens. To summarise, organic matter larger molecules (polymers) are broken down into smaller molecules (monomers) and metabolised into fermentation products, which are then used by methanogen microbes to produce methane.

Both methanogens and electrogens can use acetic acid or molecular hydrogen as an energy source. As shown in Figure 1 both types of microorganisms can use the same raw material to power their metabolism. This could be interpreted as a possible cause for substrate competition between electrogens and methanogens<sup>8,9</sup>.



**FIGURE 1:** OM is broken down by fermentative bacteria. Methanogens use the fermentation products as electron donors. The top box shows the (summarised) reactions in three different methanogen pathways: methylotrophic, acetoclastic and hydrogenotrophic<sup>8</sup>. At the bottom a (summarised) reaction occurring in a MFC. Both MFC electrogenic microorganisms, and hydrogenotrophic methanogens use hydrogen as substrate to obtain energy.

In a combined system substrate competition will lead to either a lower methane or electricity production. Within a MFC methanogenesis would act as an electrons sink reducing the coulombic efficiency (CE) of the fuel cell<sup>10</sup>. Because of this it was thought that in order to promote electrogenesis it was necessary to inhibit methanogenesis (or choose between electricity and methane). Chae *et al.*, showed that by adding 2-bromoethanesulphonate (BES) (0.1- 0.27mM) it was possible to increase CE from 35% to 70%<sup>11</sup>. Kaur *et al.*, investigated methanogenesis inhibition in a MFC through starvation and switching between open and close circuit (OC/CC) regimes<sup>12</sup>. In their study OM degraded faster at CC and methanogenesis was completely inhibit at CC. Methane production was only feasible during OC<sup>12</sup>. The last are examples showing the interference between the production of methane and electricity. More recent studies show that electrogens and methanogens can develop syntrophic relationships that result in higher methane and electricity yields. Oyiwana *et al.*, operated a MFC using glucose as substrate (feedstock) and suggested that through syntrophic interactions between *Geobacter sulfurreducens* and hydrogenotrophic methanogens it was possible to achieve higher CE. Contrary to what was shown by Chae *et al.*, Oyiwana *et al.*, showed that the addition of BES resulted in a decrease in the amount of the electricity delivered by the MFC (from 5.29 to 2W/m<sup>3</sup>). The suggested mechanism for the syntrophic interaction is interspecific hydrogen transfer (IHT), with *G. sulfurreducens* providing hydrogen (from glucose oxidation) to the hydrogenotrophic methanogens<sup>10</sup>. During the same study, in AD reactors where *G. sulfurreducens* was added, hydrogenotrophic methanogenesis was the dominant methanogenic pathway. In AD reactors without *G. sulfurreducens*, acetoclastic methanogenesis was the dominant pathway<sup>10</sup>.

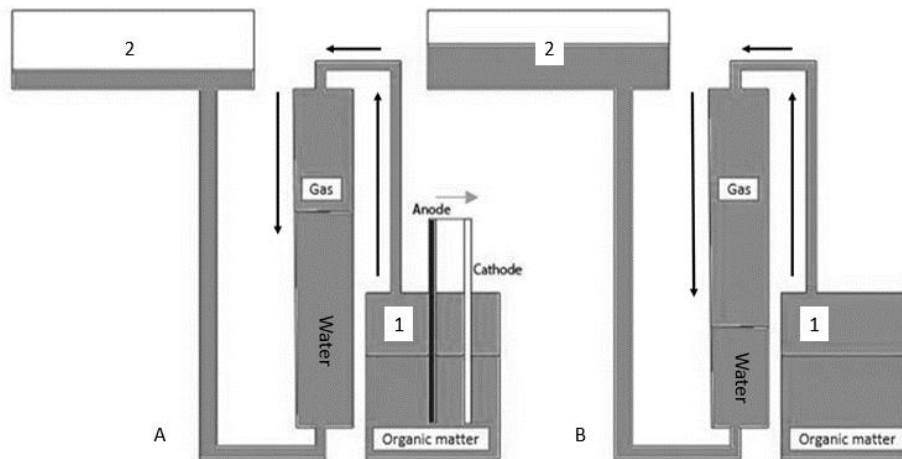
Additionally, the effect of introducing a semi-conductive material (not a whole FC) within an AD reactor has been studied before. Jing *et al.*, showed that by adding magnetite (10mg/L) to AD fed with propionate the methane yields improved by 44% in batch experiments (higher yields were also achieve when operating the reactors with acetate) and adding magnetite<sup>13</sup>. Propionate methanization is carried out through the syntrophic interaction between propionate oxidising bacteria (POB) and hydrogenotrophic methanogens. Direct interspecific electron transfer (DIET) induced by the addition of magnetite is suggested as the reason to explain the higher methane yields achieved. In their study 260 proteins were upregulated and 210 downregulated by the addition of magnetite, eleven of the upregulated proteins were enzymes

related to propionate metabolism. Cytochrome c oxidase from *Thauera* was suggested as candidate for DIET for aceticlastic methanogenesis. 43 enzymes involved in methanogenesis were affected by the addition of magnetite. Due to the presence of upregulated proteins related to methylenetetrahydromethanopterin (methylene-MPT) originated from *Methanospirillum*, *Methanospaerula* and *Methanobrevibacter*, these hydrogenotrophic genus are suggested as responsible for DIET<sup>13</sup>. In another study Rotaru *et al.*, proposed *Methanosaeta* as possible responsible for DIET<sup>9</sup>. Both DIET and IHT are present during methanization of propionate. Propionate oxidation is an endergonic reaction, because of this propionate tends to accumulate during AD, propionic acid accumulation produces a drop in pH and can lead to methanogenesis inhibition, therefore, the addition of semi-conductive materials such as magnetite that facilitate methanization of propionate can contribute to a better operation of AD reactors. It could be suggested that in a similar way to the addition of magnetite, the integration of the MFC within an AD reactor could have a relatively similar syntrophic effect by providing microorganisms with an electrons sink (anode) that can induce the oxidation of propionate, acetate and hydrogen. Within a MFC the difference in potential between the anode and the cathode providing the electromotive force to operate the MFC. It could be speculated that similar to the magnetite study, by introducing iron containing electrodes it would be possible to induce DIET and facilitate OM degradation, electrogenesis and methanogenesis. During AD of OM fermentative bacteria produce fermentation products (such as ethanol or lactic acid) that are later on used by acetogenic microorganisms to produce acetate and hydrogen, this conversion is not thermodynamically feasible at high hydrogen concentrations and therefore, acetogenesis is dependent on the hydrogen consumption rates within the reactor<sup>14</sup>. Acetogens produce acetate that can be used by aceticlastic methanogens, but, acetic acid accumulation can lead to low pH and the inhibition of aceticlastic methanogenesis. Hydrogenotrophic methanogens are also inhibit at low pH. It was shown that electrogens adapt better to low pH conditions than methanogens. It was suggested that higher methane production yields (in the AD reactors with electrodes integrated) where due to hydrogen and acetate consumption by electrogens which lead to an increase in the pH values and subsequently to the reactivation of methanogens. In the same way as the addition of magnetite, the presence of the electrodes provides the electrogens with a terminal electrodes acceptor which allows the oxidation of hydrogen and acetate until the pH values have increased to allow methanogens activation<sup>13,15,16</sup>. In the model proposed, acetate using electrogens transfer electrons from acetate to the anode, this electrons are then used by hydrogenotrophic methanogens in the cathode to produce methane by reducing carbon dioxide<sup>15</sup>. The results presented by Zhang *et al.*, and those presented by Oyiwona *et al.*, suggest that electrogenesis and methanogenesis are not mutually exclusive and contradict the substrate competition hypothesis<sup>10,15</sup>.

## MFC configuration

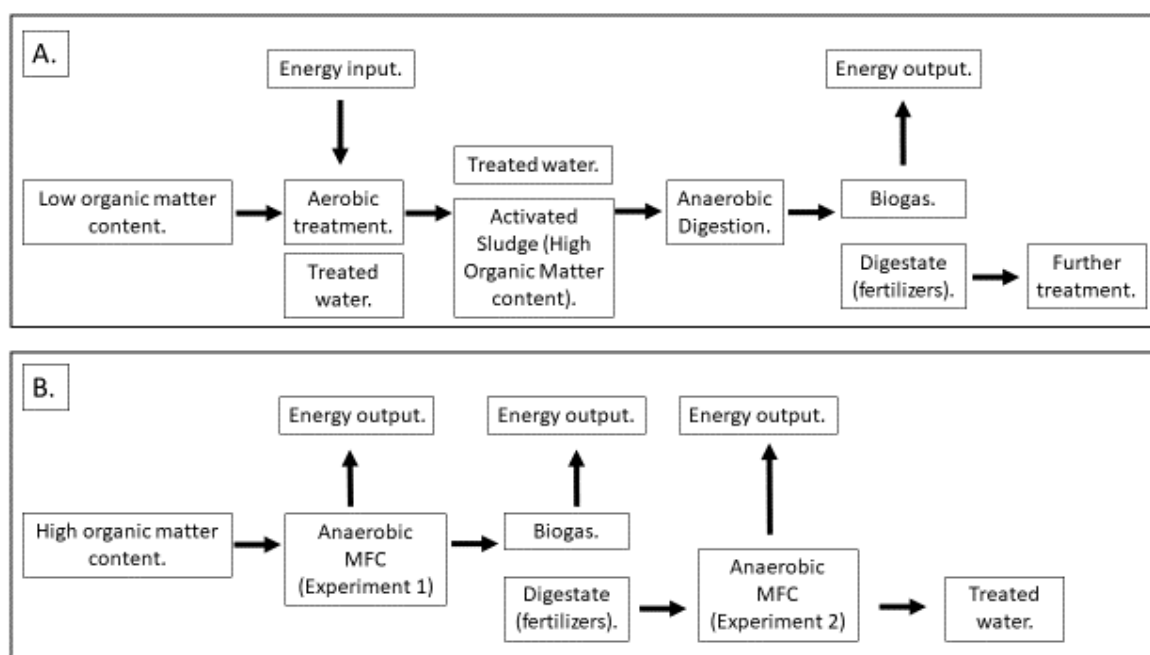
Among the different configurations analysed to main factors were identified as key to the integration of MFCs within AD reactors, the use of membranes and the shape of the fuel cell. Although using a membrane to separate the anode from the cathode yields more electricity<sup>17</sup>, it drastically increases the cost of the MFC. At present ceramics seem to be the most interesting materials to test for a large scale system set up<sup>18</sup>. With regards to the shape and design of the MFC, we prefer a tubular shape that could work as a pipe transporting water while treating it at the same time. The shape chosen has to facilitate the contact between anode and cathode of adjacent MFCs to connect them in series. At present graphite and steel

are the most common electrode materials. The use of ceramics has also been proposed for the construction of electrodes, mainly based on the use of clays with high iron content such as terracotta or goethite<sup>19</sup>. If a large scale AD system is to be integrated with MFCs, the cost of the materials has to be minimised and their efficiency has to be improved to recover more energy and facilitate a significant increase on biomethane production. A small increase on methane production can have a significant economic impact in an AD plant operating with thousands of tonnes of organic matter per year, therefore it is important to explore the impact that the use of MFCs could have on biogas production. For this a biomethane potential test will be developed in parallel with a MFC operation.



**FIGURE 2:** Schematic representation of the laboratory system proposed for evaluating the integration of MFCs and AD. AD reactors A) with MFC (left) and B) without MFC (right). The gas produced (1) in each reactor (500mL) flows up to each of their columns (1L) pushing the red liquid used as indicator towards the reservoir (2). Anode and cathode are connected with copper wire to a data-logger to collect the information about voltage and electricity generation.

Figure three shows the potential that the integration of MFCs in WWT facilities can have over energy flows in the system. The potential of recovering the energy that is contained in the organic waste produced by a city or by a country is unknown, a study from Saudi Arabia estimates that this country could inject into the grid 637MWe (by2035) from the bioelectrochemical treatment of its domestic water<sup>20</sup>.



**FIGURE 1:** Traditional WWT of organic matter (A) requires energy input to supply oxygen to the aerobic microorganisms. The proposed arrangement for the treatment of OM, through the combination of MFCs and AD (B), could be integrated during different stages of the WWT process.

## CONCLUSIONS

Our literature review suggest that it might be possible to produce biogas while at the same time sustain a constant electricity generation through the integration between a MFC and an AD reactor, without affecting negatively the final biogas production or its composition. Although some authors have proposed that methane production constrains electricity production, the opposite has been observed in a few studies using semi conductive materials and electrochemical devices. Because of this we consider important to further research into a way to integrate these two waste to energy technologies.

Syntrophic interactions between microorganisms producing electricity and those producing methane have been suggested by other authors as a possible explanation for the higher biogas yields in AD reactors operating with a BED integrated or with a semi-conductive material such as magnetite reported by other authors. Hydrogen and electrons transfer between species are the possible mechanisms facilitating this interactions, at present it is not clear how to exploit this in order to achieve higher biomass conversion rates.

The operation of an AD-MFC integrated system could allow the small scale production of bioelectricity within urban environments where the space is limited. Electricity production for small appliances would not be depending on the combustion of the biogas. At present the cost of a generator as well as the presence of hydrogen sulphide in the biogas, limit the small scale production of energy. It is important to research on alternatives such as MFCs that allow us to convert organic matter into electricity directly, without the need of a generator.

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